

CLUSTERING OF LOW-REDSHIFT ( $Z \leq 2.2$ ) QUASARS FROM THE SLOAN DIGITAL SKY SURVEYNICHOLAS P. ROSS<sup>1</sup>, YUE SHEN<sup>2</sup>, MICHAEL A. STRAUSS<sup>2</sup>, DANIEL E. VANDEN BERK<sup>1</sup>, ANDREW J. CONNOLLY<sup>3</sup>, GORDON T. RICHARDS<sup>4</sup>, DONALD P. SCHNEIDER<sup>1</sup>, DAVID H. WEINBERG<sup>5</sup>, PATRICK B. HALL<sup>6</sup>, NETA A. BAHCALL<sup>2</sup>, ROBERT J. BRUNNER<sup>7</sup>*Draft version March 18, 2009*

## ABSTRACT

We present measurements of the quasar two-point correlation function,  $\xi_Q$ , over the redshift range  $0.3 \leq z \leq 2.2$  based upon data from the Sloan Digital Sky Survey (SDSS). Using a homogeneous sample of 30,239 quasars with spectroscopic redshifts from the Data Release 5 Quasar Catalogue, our study represents the largest sample used for this type of investigation to date. With this redshift range and an areal coverage of  $\approx 4,000 \text{ deg}^2$ , we sample over  $25 h^{-3} \text{ Gpc}^3$  (comoving) of the Universe in volume, assuming the current  $\Lambda$ CDM cosmology. Over this redshift range, we find that the redshift-space correlation function,  $\xi(s)$ , is adequately fit by a single power-law, with  $s_0 = 5.95 \pm 0.45 h^{-1} \text{ Mpc}$  and  $\gamma_s = 1.16^{+0.11}_{-0.16}$  when fit over  $1.0 \leq s \leq 25.0 h^{-1} \text{ Mpc}$ . We find no evidence for deviation from  $\xi(s) = 0$  at scales of  $s > 100 h^{-1} \text{ Mpc}$ , but do observe redshift-space distortions in the 2-D  $\xi(r_p, \pi)$  measurement. Using the projected correlation function,  $w_p(r_p)$ , we calculate the real-space correlation length,  $r_0 = 5.45^{+0.35}_{-0.45} h^{-1} \text{ Mpc}$  and  $\gamma = 1.90^{+0.04}_{-0.03}$ , over scales of  $1.0 \leq r_p \leq 130.0 h^{-1} \text{ Mpc}$ . Dividing the sample into redshift slices, we find very little, if any, evidence for the evolution of quasar clustering, with the redshift-space correlation length staying roughly constant at  $s_0 \sim 6 - 7 h^{-1} \text{ Mpc}$  at  $z \lesssim 2.2$  (and only increasing at redshifts greater than this). We do, however, see tentative evidence for evolution in the real-space correlation length,  $r_0$ , at  $z > 1.7$ . Our results are consistent with those from the 2QZ survey and previous SDSS quasar measurements using photometric redshifts. Comparing our clustering measurements to those reported for X-ray selected AGN at  $z \sim 0.5 - 1$ , we find reasonable agreement in some cases but significantly lower correlation lengths in others. Assuming a standard  $\Lambda$ CDM cosmology, we find that the linear bias evolves from  $b \sim 1.4$  at  $z = 0.5$  to  $b \sim 3$  at  $z = 2.2$ , with  $b(z = 1.27) = 2.06 \pm 0.03$  for the full sample. We compare our data to analytical models and infer that quasars inhabit dark matter haloes of constant mass  $M_{\text{halo}} \sim 2 \times 10^{12} h^{-1} M_\odot$  from redshifts  $z \sim 2.5$  (the peak of quasar activity) to  $z \sim 0$ ; therefore the ratio of the halo mass for a typical quasar to the mean halo mass at the same epoch drops with decreasing redshift. The measured evolution of the clustering amplitude is in reasonable agreement with recent theoretical models, although measurements to fainter limits will be needed to distinguish different scenarios for quasar feeding and black hole growth.

*Subject headings:* clustering – quasars: general – cosmology: observations – large-scale structure of Universe. general – surveys

## 1. INTRODUCTION

Understanding how and when the structures in the local Universe formed from the initial conditions present in the early Universe is one of the fundamental goals of modern observational cosmology. Tracing the evolution of clustering with cosmic epoch offers the potential to understand the growth of structure and its relation to the energy and matter content of the Universe, including the relationship between the dark matter and the luminous

galaxies and quasars that we observe.

As such, one of the primary science goals of the Sloan Digital Sky Survey (SDSS; York et al. 2000) is to measure the large-scale distribution of galaxies and quasars, and in particular, to determine the spatial clustering of quasars as a function of redshift. Shen et al. (2007) report on the clustering of high redshift ( $z \geq 2.9$ ) quasars from the SDSS; in this paper, we investigate the spatial clustering from redshift  $z = 2.2$  to the present day, i.e. the evolution of quasar clustering over nearly 80% of the age of the Universe (the gap in redshift being a consequence of the optical selection techniques used in the SDSS).

Due to their high intrinsic luminosities, quasars are seen to large cosmological distances, and are thus good probes of large-scale structure (LSS) and its evolution. However, until recently, quasar studies were plagued by low-number statistics, leading to shot noise, and samples covered only small areas of sky, leading to sample variance. With the advent of large solid angle ( $\gtrsim 1000 \text{ deg}^2$ ) surveys with efficient selection techniques, these limitations have been overcome, and the number of known

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quasars has increased by more than an order of magnitude in the last decade, thanks mainly to the 2dF QSO Redshift Survey (2QZ; Boyle et al. 2000; Croom et al. 2004) and the SDSS. The latest SDSS quasar catalogue (Schneider et al. 2007) contains nearly 80 000 objects. Using the data from these large surveys, we are now in a position to make high-precision measurements of quasar clustering properties.

The two-point correlation function (2PCF),  $\xi$ , is a simple but powerful statistic commonly employed to quantify the clustering properties of a given class of object (Peebles 1980). The observed value of  $\xi$  for quasars can be related to the underlying (dark) matter density distribution via

$$\xi(r)_{\text{quasar}} = b_Q^2 \xi(r)_{\text{matter}} \quad (1)$$

where  $\xi(r)_{\text{matter}}$  is the mass correlation function and  $b_Q$  is the linear bias parameter for quasars. Although equation (1) defines  $b_Q$ , and there are theoretical arguments suggesting that  $b_Q$  is scale-independent on large scales, e.g. Scherrer & Weinberg (1998), we do not know *a priori* if this is the case.

With certain reasonable assumptions, the measurement and interpretation of the bias can lead to determination of the dark matter halo properties of quasars and to quasar lifetimes ( $t_q$ , Martini & Weinberg 2001; Haiman & Hui 2001). In the standard scenario, quasar activity is triggered by accretion onto a central, supermassive black hole (SMBH, e.g. Salpeter 1964; Lynden-Bell 1969; Rees 1984). Given the possible connection between the SMBH and host halo, and the fact that halo properties are correlated with the local density contrast, clustering measurements can be used to constrain this potential halo-SMBH connection and provide an insight into quasar and black hole physics (e.g. Baes et al. 2003; Wyithe & Loeb 2005; Wyithe & Padmanabhan 2006; Adelberger & Steidel 2005b; Fine et al. 2006; da Ángela et al. 2008). This information, combined with the quasar luminosity function (QLF), constrains  $\eta$ , the fraction of the Eddington luminosity at which quasars shine, and their duty cycle (Wyithe & Loeb 2005; Shankar et al. 2007).

Early measurements of the quasar 2PCF (e.g. Arp 1970; Hawkins & Reddish 1975; Osmer 1981; Shanks et al. 1983, 1987) measured statistically significant clustering on scales of a few  $h^{-1}$  Mpc, for both the quasar auto-correlation function and cross-correlation with galaxies. This result has been confirmed with data from more recent surveys, (e.g. Croom et al. 2005; Porciani et al. 2004). The Quasar 2PCF is typically fit to a single power law of the form,

$$\xi(r) = (r/r_0)^{-\gamma} \quad (2)$$

over the range  $1 h^{-1} \text{ Mpc} \leq r \leq 100 h^{-1} \text{ Mpc}$ . Here,  $r_0$  is the correlation length quoted in comoving coordinates and  $\gamma$  is the power-law slope. Typical measured correlation lengths and slopes for quasars at redshift  $z \sim 1.5$  are  $r_0 = 5 - 6 h^{-1} \text{ Mpc}$  and  $\gamma \sim 1.5$ , respectively.

The evolution of the quasar correlation function has been disputed for a long time, with some authors reporting that  $r_0$  either decreased or only weakly evolved with redshift (e.g. Iovino & Shaver 1988; Croom & Shanks 1996), while others reported an increase with redshift

(e.g. Kundic 1997; La Franca et al. 1998). However, with the advent of the 2QZ Survey,  $r_0$  has been shown to evolve at the  $\sim 90 - 99\%$  confidence level, in the sense that quasar clustering increases with redshift, although the actual degree of evolution is weak (Croom et al. 2001; Porciani et al. 2004; Croom et al. 2005). In particular, Croom et al. (2005) used over 20 000 objects from the final 2QZ dataset to measure the redshift-space two-point correlation function,  $\xi(s)$ , over the redshift range  $0.3 < z < 2.2$  and found a significant increase in the clustering amplitude at high redshift. The quasar bias, where the bias depends on the underlying CDM model such that a constant  $r_0$  can imply a strongly varying  $b$ , was found to be a strong function of redshift, with an empirical dependence of

$$b_Q(z) = (0.53 \pm 0.19) + (0.289 \pm 0.035)(1+z)^2. \quad (3)$$

These values were used to derive the mean dark matter halo (DMH) mass occupied by quasars, giving a redshift-independent value of  $M_{\text{DMH}} = (3.0 \pm 1.6) \times 10^{12} h^{-1} M_\odot$ . Independent analysis of the 2QZ data by Porciani et al. (2004) confirmed these findings.

Using the SDSS, Shen et al. (2007) found that redshift  $2.9 \leq z \leq 5.4$  quasars are significantly more clustered than their  $z \sim 1.5$  counterparts, having a real-space correlation length and power-law slope of  $r_0 = 15.2 \pm 2.7 h^{-1} \text{ Mpc}$  and  $\gamma = 2.0 \pm 0.3$ , respectively, over the scales  $4 h^{-1} \text{ Mpc} \leq r_p \leq 150 h^{-1} \text{ Mpc}$  (where  $r_p$  is the separation from the projected correlation function,  $w_p(r_p)$ ). Shen et al. (2007) also found that bias increases with redshift, with,  $b_Q \sim 8$  at  $z = 3.0$  and  $b_Q \sim 16$  at  $z = 4.5$ .

Myers et al. (2006, 2007), also using SDSS data, examined the clustering of photometrically-selected quasar candidates over  $\sim 50 h^{-1} \text{ kpc}$  to  $\sim 20 h^{-1} \text{ Mpc}$  scales. In this sample, quasar redshifts were assigned from photometric rather than spectral information (Richards et al. 2001). They found that the linear bias,  $b_Q$ , increases with redshift, from  $b_Q = 1.93$  at redshifts  $0.4 \leq z < 1.0$  to  $b_Q = 2.84$  at  $2.1 \leq z < 2.8$ , consistent with equation (3) (Fig. 4 of Myers et al. 2007).

Padmanabhan et al. (2008) measured the clustering of photometrically-selected luminous red galaxies (LRGs) around a low redshift,  $0.2 < z < 0.6$ , sample of quasars, with both LRG and quasar samples coming from the SDSS. They determined a large-scale quasar bias  $b_Q = 1.09 \pm 0.15$  at a median redshift of  $z = 0.43$ . After taking into account measurement and interpretation subtleties, the results from Padmanabhan et al. (2008), are in qualitative agreement with those from Serber et al. (2006), who find that  $M_i \leq -22$ ,  $z \leq 0.4$  quasars are located in higher local galaxy overdensities than typical  $L^*$  galaxies. Serber et al. (2006) suggested that quasars typically reside in  $L^*$  galaxies, but have a local excess of neighbours within  $\sim 0.15 - 0.7 h^{-1} \text{ Mpc}$ , which contributes to the triggering of quasar activity through mergers and other interactions. Strand et al. (2008) using photometric redshift cuts, confirm the basic overdensity values measured by Serber et al. (2006). Hennawi et al. (2006), Myers et al. (2007) and Myers et al. (2008) reached similar conclusions by examining pairs of quasars on  $< 1 h^{-1} \text{ Mpc}$  scales. The quasar correlation function shows a small scale excess over a power law, and Hennawi et al. (2006) suggested that the small-scale excess can be at-

tributed to dissipative interaction events that trigger quasar activity in rich environments.

Due to the evolution of the quasar luminosity function and the flux-limited nature of most quasar samples, there is a strong correlation between redshift and luminosity in these samples, making it difficult to isolate luminosity dependence of clustering from redshift dependence. Recently, da Ângela et al. (2008) combined data from the 2QZ and the 2SLAQ Survey (2dF-SDSS LRG And QSO Survey; Croom et al. 2008), to investigate quasar clustering and break this degeneracy. da Ângela et al. (2008) estimate the mass of the dark matter haloes which quasars inhabit to be  $\sim 3 \times 10^{12} h^{-1} M_{\odot}$ , in agreement with Croom et al. (2005), a value that does not evolve strongly with redshift or depend on QSO luminosity. Their results also suggest that quasars of different luminosities may contain black holes of similar mass.

There have also been recent advances in theoretical predictions of the quasar correlation function and its evolution with redshift (Lidz et al. 2006; Hopkins et al. 2007; Shankar et al. 2007; Hopkins et al. 2008; Basilakos et al. 2008) and we discuss these models in more detail in Sections 4 and 5.

In this paper, we shall measure the quasar 2PCF for redshifts  $z \leq 2.2$ , using the largest sample of spectroscopically identified quasars to date. We will investigate the dependence of quasar clustering strength with redshift and luminosity, allowing tests of current quasar formation and evolution models.

This paper is organised as follows. In Section 2 we present our data sample, mentioning several effects that could give rise to systematics in the measurements. In Section 3 we briefly describe the techniques involved in measuring the two-point correlation function and in Section 4 we present our results. In Section 5 we compare and contrast our evolutionary results with recent observational results in the literature, and we conclude in Section 6. Appendix A gives technical details for the SDSS, Appendix B describes our error analysis and Appendix C carries out a series of systematic checks.

In our companion paper (Shen et al. 2009), we expand our investigations on the clustering of SDSS quasars. Using the same data as we examine here, Shen et al. study the dependence of quasar clustering on luminosity, virial black hole mass, quasar colour and radio loudness.

We assume the currently preferred flat, “Lambda Cold Dark Matter” ( $\Lambda$ CDM) cosmology where  $\Omega_b = 0.042$ ,  $\Omega_m = 0.237$ ,  $\Omega_{\Lambda} = 0.763$  (Sánchez et al. 2006; Spergel et al. 2007) and quote distances in units of  $h^{-1}$  Mpc to aid in ease of comparisons with previous results in the literature. Since we are measuring objects with redshifts resulting from the Hubble flow, all distances herein are given in comoving coordinates. Where a value of Hubble’s Constant is assumed e.g. for absolute magnitudes, this will be quoted explicitly. Our magnitudes are based on the AB zero-point system (Oke & Gunn 1983).

## 2. DATA

Much care must be taken when constructing a dataset that is valid for a statistical analysis. In this section and Appendix A we describe the various samples we use to investigate potential systematic effects in our clustering measurements. Appendix A provides some of the rele-

vant technical details of the SDSS, discussing the Catalogue Archive Server (CAS) and the SDSS Survey geometry.

### 2.1. The Sloan Digital Sky Survey

The SDSS uses a dedicated 2.5m wide-field telescope (Gunn et al. 2006) to collect light for 30 2k×2k CCDs (Gunn et al. 1998) over five broad bands - *ugriz* (Fukugita et al. 1996) - in order to image  $\sim \pi$  steradians of the sky. The imaging data are taken on dark photometric nights of good seeing (Hogg et al. 2001) and are calibrated photometrically (Smith et al. 2002; Ivezić et al. 2004; Tucker et al. 2006; Padmanabhan et al. 2008), and astrometrically (Pier et al. 2003), and object parameters are measured (Lupton et al. 2001; Stoughton et al. 2002).

Using the imaging data, quasar target candidates are selected for spectroscopic observation based on their colours, magnitudes and detection in the FIRST radio survey (Becker et al. 1995), as described by Richards et al. (2002). Unless stated otherwise, all quoted SDSS photometry has been corrected for Galactic extinction following Schlegel et al. (1998). Here we are concerned with only those quasars selected from the main quasar selection (Richards et al. 2002). Low-redshift,  $z \lesssim 3$ , quasar targets are selected based on their location in *ugri*-colour space and the high-redshift,  $z \gtrsim 3$ , objects in *griz*-colour space. Quasar candidates passing the *ugri*-colour selection are selected to a flux limit of  $i = 19.1$ , but since high-redshift quasars are rare, objects lying in regions of colour-space corresponding to quasars at  $z > 3$  are targetted to  $i = 20.2$ . Furthermore, if an unresolved,  $i \leq 19.1$  SDSS object is matched to within  $2''$  of a source in the FIRST catalogue, it is included in the quasar selection.

A tiling algorithm then assigns these candidates to specific spectroscopic plates, in order to maximise target completeness (Blanton et al. 2003). Each  $3^\circ$  diameter spectroscopic plate holds 640 fibres and quasar candidates are allocated at a density of approximately 18 fibers  $\text{deg}^{-2}$ . No two fibres can be placed closer than  $55''$ , corresponding to  $\sim 0.7 h^{-1}$  Mpc at  $\langle z \rangle = 1.27$ , the mean redshift of our sample (Fig. 23). In the case of conflicts because of this  $55''$  constraint, the main quasar selection candidates were given targetting priority over the MAIN galaxy and LRG survey targets (Strauss et al. 2002; Eisenstein et al. 2001, respectively). Therefore, excluding subtle effects due to gravitational lensing (Scranton et al. 2005; Mountrichas & Shanks 2007), the LSS ‘footprint’ of these foreground galaxies should not affect our LSS quasar measurements. Some targets, including brown dwarf and hot subdwarf calibration star candidates, were given higher priority than the main quasar candidates. However, since the surface density of these Galactic objects is very low ( $\ll 1 \text{ deg}^{-2}$ ), this should not have any significant impact on our results. We investigate the effects of quasar-quasar fibre collisions in Appendix C.6.

### 2.2. Quasar Samples

For our analysis, we use the SDSS Data Release Five (DR5; Adelman-McCarthy et al. 2007) and select quasars from the latest version of the quasar catalogue (DR5Q; Schneider et al. 2007). This catalogue consists

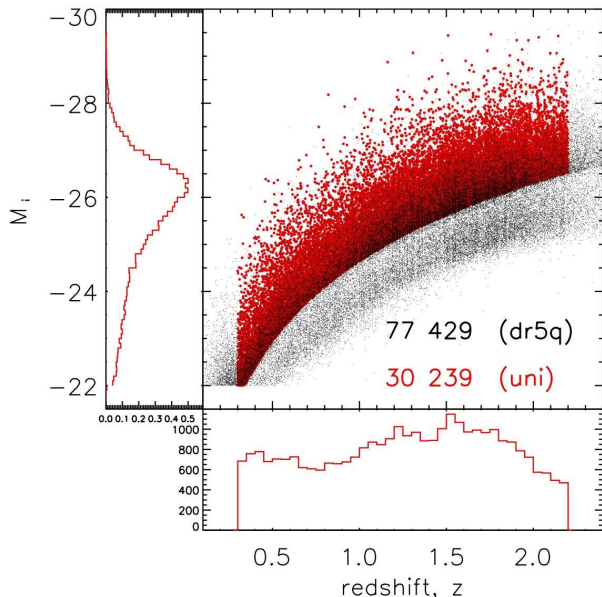


FIG. 1.— The SDSS DR5 Quasar  $L-z$  plane for the DR5Q (black points) and the UNIFORM sample (red points). The affect of the  $i = 19.1$  magnitude limit can clearly be seen.  $M_i$  is the  $i$ -band absolute magnitude at the plotted redshift where we use the  $K$ -correction given by Table 4 of Richards et al. (2006).

of spectroscopically identified quasars that have luminosities larger than  $M_i = -22.0$  (measured in the rest frame) and at least one emission line with FWHM larger than  $1000 \text{ km s}^{-1}$ . Every object in the DR5Q had its spectrum manually inspected. There are 77 429 confirmed quasars over the  $5\,740 \text{ deg}^2$  spectroscopic DR5 footprint; the 65 660 DR5Q quasars with redshifts  $z \leq 2.2$  will be the parent sample we use in this investigation.

At  $z \geq 2.2$  the “ultra-violet excess” (UVX) method of selecting quasars begins to fail due to the Ly $\alpha$ -forest suppressing flux as it moves through the SDSS  $u$ -band, and quasars have colours similar to those of F-stars (Fan 1999). Thus, for  $2.2 < z \leq 2.9$ , the completeness of the survey is dramatically lowered as is discussed in detail by Richards et al. (2006). A lower redshift limit of  $z = 0.30$  is chosen to match that of the 2QZ. Therefore, although we will present results in the redshift ranges  $z < 0.30$  and  $2.2 < z \leq 2.9$ , we will not place strong significance on these data. The number of quasars used in this study is twice that of the previous largest quasar survey, the 2QZ (Boyle et al. 2000; Croom et al. 2005) and allows division of our sample in luminosity and redshift bins while retaining statistical power. As shown in Sections 4 and 5, these new data complement the existing 2QZ and 2SLAQ quasar survey results, and together improve constraints on theoretical models.

We construct two subsamples from DR5Q. The first is designated as the “PRIMARY” Sample, which will include those objects in the DR5Q which were targetted as primary quasar candidates (Richards et al. 2002), having satisfied one, or more, of the TARGET\_QSO, TARGET\_HI2 or TARGET\_FIRST selections (see Stoughton et al. 2002, Section 4.8, for more details on these flags). The SDSS quasar survey was designed to be complete in the primary sample, and no attempt was made at completeness for the quasars selected by other means. In total there are 55 577 quasars in the DR5Q that had their target

flags set to one (or more) of these primary flags, with 46 272 quasars satisfying our high redshift limit (Table 1).

The SDSS quasar selection algorithm was in flux in the early part of the survey, and was only finalised after DR1. We define the “UNIFORM” sample to be those primary objects selected with this final version. The UNIFORM sample is flux limited to  $i = 19.1$  at  $z \leq 2.9$  and contains 38 208 objects, dropping to 31 290 when a redshift cut of  $z \leq 2.2$  is applied. We show the distribution of objects in the redshift-luminosity plane for the full DR5Q and  $0.30 \leq z \leq 2.2$  UNIFORM sample in Figure 1. We will use both the PRIMARY and the UNIFORM samples in what follows, but will find inconsistent results between the two samples at scales  $\gtrsim 60 h^{-1} \text{ Mpc}$ . This is investigated further in Appendix C.

The quasar correlation function is sensitive to a number of potential systematic effects, including bad photometry and improperly corrected dust reddening. Since quasars are selected by their optical colors, we shall perform checks on both our PRIMARY and UNIFORM samples in Appendix C to see what effect regions with poor photometry (as defined by Richards et al. 2006; Shen et al. 2007) has on our clustering measurements.

While all selection for the quasar sample is undertaken using dereddened colors (Richards et al 2001), if there remain systematic errors in the reddening model they can induce excess power into the clustering in a number of different ways. Appendix C describes how these effects affect our  $\xi(s)$  measurements and the interpretations based thereon. Briefly, we find that: the UNIFORM sample is the most stable sample for our studies; reddening and bad fields produce insignificant effects to our measurements; our results are insensitive to the choice of the upper bound of the integral in equation (9) ( $\pi_{\text{max}}$ , see Section 3.2) and the comoving  $z_{\text{max}}$  and fibre collisions are not a concern on the scales we investigate.

### 3. TECHNIQUES

In this section we describe the techniques we shall use to calculate the Quasar  $z \leq 2.2$  2PCF. The interested reader is referred to the comprehensive texts of Peebles (1980, 1993); Peacock (1999); Coles & Lucchin (2002) and Martínez & Saar (2002) for full details on the 2PCF.

#### 3.1. Estimating the 2-Point Quasar Correlation Function

In practice,  $\xi$  is measured by comparing the actual quasar distribution to a catalogue of “random” points, which have the same selection function, angular mask and radial distribution as the data, but are spatially distributed in a “random” manner - i.e. are not clustered. The construction of this random sample shall be described in Section 3.2.

We use the estimator of Landy & Szalay (1993) to calculate  $\xi$ , as this has been found to be the most reliable estimator for 2PCF studies (Kerscher et al. 2000). Comparing our results to those using the estimators of Davis & Peebles (DP, 1983) and Hamilton (1992), we find the DP estimator causes systematic errors on large scales with too much power at  $s \geq 40 h^{-1} \text{ Mpc}$ , as this estimator is less robust to errors in the estimation of mean density. The LS estimator is given by,

TABLE 1  
THE SDSS SPECTROSCOPIC QUASAR SAMPLES

Sample Description	Area /deg <sup>2</sup>	Number in sample	$z_{\min}$	$z_{\max}$	$z_{\text{med}}$
DR5Q	$\approx 5740$	77 429	0.078	5.414	1.538
" $z \leq 2.9$		71 375	0.078	2.900	1.372
" $0.3 \leq z \leq 2.9$		69 692	0.300	2.900	1.400
" $z \leq 2.2$		65 660	0.078	2.200	1.278
" $0.3 \leq z \leq 2.2$		63 977	0.300	2.200	1.306
PRIMARY	5713	55 577	0.080	5.414	1.543
" $z \leq 2.9$		50 062	0.080	2.900	1.326
" $0.3 \leq z \leq 2.9$		48 526	0.300	2.900	1.360
" $z \leq 2.2$		46 272	0.080	2.200	1.234
" $0.3 \leq z \leq 2.2$		44 736	0.300	2.200	1.268
UNIFORM	4013	38 208	0.084	5.338	1.575
" $z \leq 2.9$		33 699	0.084	2.900	1.319
" $0.3 \leq z \leq 2.9$		32 648	0.300	2.900	1.234
" $z \leq 2.2$		31 290	0.084	2.200	1.354
" <b><math>0.3 \leq z \leq 2.2</math></b>		<b>30 239</b>	<b>0.300</b>	<b>2.200</b>	<b>1.269</b>

NOTE. — The SDSS Spectroscopic Quasar Samples used in our analysis, with minimum, maximum and median redshifts. The DR5Q is the catalogue presented in Schneider et al. (2007), while the PRIMARY and UNIFORM samples are described in Section 2. The results for the UNIFORM sample indicated in boldface are given in Section 4.

$$\xi_{LS}(s) = 1 + \left(\frac{N_{rd}}{N}\right)^2 \frac{DD(s)}{RR(s)} - 2 \left(\frac{N_{rd}}{N}\right) \frac{DR(s)}{RR(s)} \quad (4)$$

$$\equiv \frac{\langle DD \rangle - \langle 2DR \rangle + \langle RR \rangle}{\langle RR \rangle} \quad (5)$$

Here  $N$  and  $N_{rd}$  are the number of data and random points in the sample,  $DD(s)$  is the number of data-data pairs with separation between  $s$  and  $s + \Delta s$  in the given catalogue,  $DR(s)$  is the number of data-random pairs, and  $RR(s)$  the number of random-random pairs. The angled brackets denote the suitably normalised pair counts, since we employ at least twenty times more random points than data in order to reduce Poisson noise. We choose our bins to be logarithmically spaced, with widths of  $\Delta \log(s/h^{-1} \text{ Mpc}) = 0.1$ .

The measurement of a quasar redshift will not only have a (large) component due to the Hubble expansion, but also components due to the intrinsic peculiar velocities and redshift errors associated with the individual quasar. The peculiar velocities can be seen in the redshift-space correlation function, both at small and large scales (see Section 4). However, as noted in Schneider et al. (2007) and discussed in detail in Shen et al. (2007, Appendix A), quasar redshift determination can have uncertainties of  $\sigma_v = 500 - 1450 \text{ km s}^{-1}$  and hence  $\sigma_z = 0.003 - 0.01$ , and these redshift errors will dominate any determination of the peculiar velocity signal.

The real-space correlation function,  $\xi(r)$ , is what would be measured in the absence of any redshift-space distortions. We can measure  $\xi(r)$  by projecting out the effects of peculiar velocities and redshift errors along the line of sight.

One can resolve the redshift-space separation,  $s$ , between two quasars into two components,  $r_p$  and  $\pi$ , where  $r_p$  is the separation between two objects *perpendicular* to the line-of-sight and  $\pi$  is the separation *parallel* to the line-of-sight. Thus,

$$s^2 = r_p^2 + \pi^2 \quad (6)$$

(where  $r_p \equiv \sigma$  is also found in the literature). The ‘2-D’ redshift-space correlation function,  $\xi(r_p, \pi)$ , can be calculated as before,

$$\xi_{LS}(r_p, \pi) = \frac{\langle DD(r_p, \pi) \rangle - \langle 2DR(r_p, \pi) \rangle + \langle RR(r_p, \pi) \rangle}{\langle RR(r_p, \pi) \rangle} \quad (7)$$

where the bin sizes are now chosen to be  $\Delta \log(r_p/h^{-1} \text{ Mpc}) = \Delta \log(\pi/h^{-1} \text{ Mpc}) = 0.2$ .

Redshift-space distortions affect only the radial component of  $\xi(r_p, \pi)$ ; thus by integrating along the line-of-sight direction,  $\pi$ , we obtain the projected correlation function,

$$w_p(r_p) = 2 \int_0^\infty \xi(r_p, \pi) d\pi. \quad (8)$$

In practice we set the upper limit on the integral to be  $\pi_{\max} = 10^{1.8} = 63.1 h^{-1} \text{ Mpc}$  and show that although varying this limit does cause some difference to the deduced  $w_p(r_p)$ , it does not cause significant changes to the 2PCF over the scales of interest for our studies (Appendix C.7).

The integral in equation 8 can be rewritten in terms of  $\xi(r)$  (Davis & Peebles 1983),

$$w_p(r_p) = 2 \int_0^{\pi_{\max}} \frac{r \xi(r)}{\sqrt{(r^2 - r_p^2)}} dr. \quad (9)$$

If we assume that  $\xi(r)$  is a power law of the form,  $\xi(r) = (r/r_0)^{-\gamma}$  (which, as we shall find later, is a fair assumption), then equation 9 can be integrated analytically, such that with  $\pi_{\max} = \infty$ ,

$$w_p(r_p) = r_0^\gamma r_p^{1-\gamma} \left[ \frac{\Gamma(\frac{1}{2}) \Gamma(\frac{\gamma-1}{2})}{\Gamma(\frac{\gamma}{2})} \right] \equiv r_0^\gamma r_p^{1-\gamma} A(\gamma), \quad (10)$$

where  $\Gamma(x)$  is the Gamma function.

In linear theory and in the absence of small-scale velocities and redshift errors, the redshift-space and real-space correlation function can be related via

$$\xi(s) = \xi(r) \left( 1 + \frac{2}{3} \beta(z) + \frac{1}{5} \beta^2(z) \right), \quad (11)$$

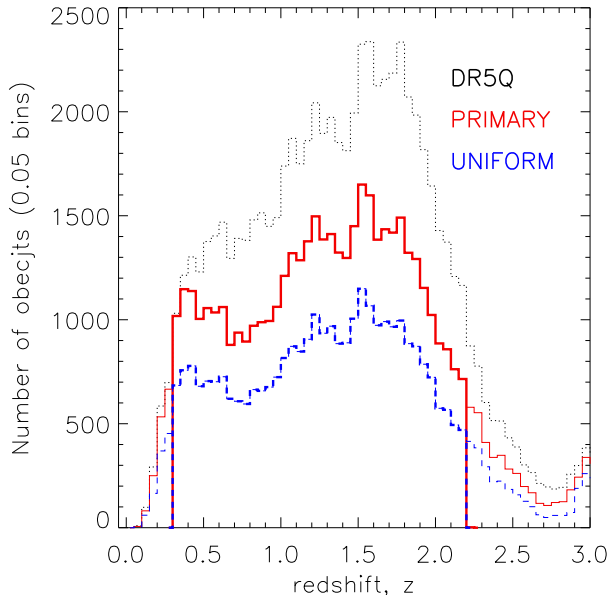


FIG. 2.— The SDSS DR5 Quasar  $N(z)$ . The solid (red) histogram shows the quasar redshift distribution for the PRIMARY sample, while the dashed (blue) histogram shows the redshift distribution for the UNIFORM sample. The thin lines for both PRIMARY and UNIFORM do not include the  $0.3 < z \leq 2.2$  cuts. As a comparison, the full DR5Q sample is given by the dotted (black) histogram. where

$$\beta(z) = \frac{\Omega_m(z)^{0.55}}{b(z)} \quad (12)$$

parametrizes the ‘flattening’ at large scales of the correlation function due to the infall of matter from underdense to overdense regions. The value of  $\beta(z)$  has traditionally been measured via fits to observed data (e.g. Kaiser 1987; Fisher et al. 1994; Peacock et al. 2001; Hawkins et al. 2003; Ross et al. 2007; Guzzo et al. 2008).

### 3.2. Construction of the Random Catalogue

As mentioned above, to calculate  $\xi$  in practice, one needs to construct a random catalogue of points that mimics the data in every way, bar its clustering signal. The angular mask and completeness for the PRIMARY and UNIFORM sample is described in detail in Appendix A.

The radial distribution of the sample is measured from the data themselves. Figure 2 shows the  $N(z)$  distribution of the DR5Q quasars from our samples. We fit a tenth-order polynomial to both the PRIMARY and UNIFORM samples, which we use to generate the random sample redshift distribution. This method has proved reliable in previous quasar clustering studies (e.g. Croom et al. 2005; da Ângela et al. 2008).

### 3.3. Errors and Covariances

Recent studies (e.g. Scranton et al. 2002; Zehavi et al. 2002; Myers et al. 2006; Ross et al. 2007) have employed three main methods, *Poisson*, *Field-to-Field* and *Jackknife* to estimate errors in correlation function measurements. The ‘simplest’ of these is the Poisson error described by Peebles (1973); this is the Poisson noise due to the number of pairs in the sample,

$$\sigma_{\text{Poi}} = \frac{1 + \xi(s)}{\sqrt{DD(s)}}. \quad (13)$$

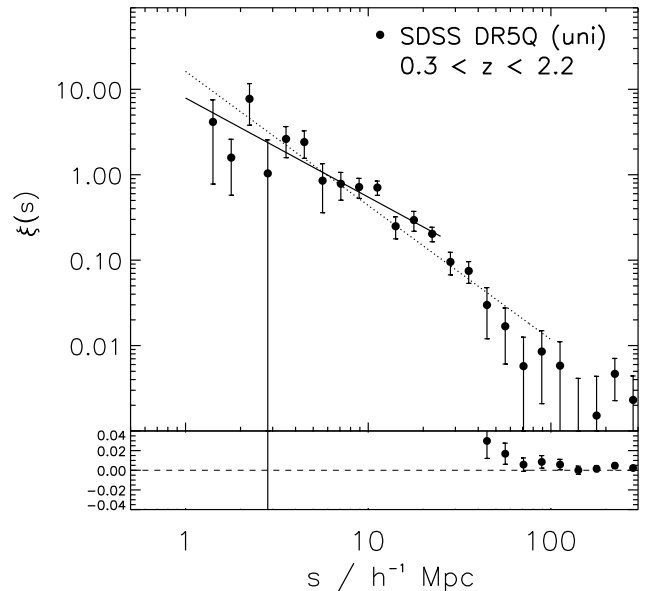


FIG. 3.— The SDSS Quasar redshift-space 2PCF,  $\xi(s)$ , from the UNIFORM sample (filled circles). The solid line shows the best fit single power-law model over  $1 \leq s \leq 25.0 \, h^{-1} \text{ Mpc}$ , while the dotted line shows the best fit single power-law model over  $1 \leq s \leq 100.0 \, h^{-1} \text{ Mpc}$ . The lower panel shows the  $\xi(s)$  behaviour near zero on a linear scale. The quoted errorbars are jackknife errors from the diagonal elements of the covariance matrix.

This expression should be valid at smaller scales where the number of pairs is small and most pairs are independent (i.e. few quasars are involved in more than one pair; Shanks & Boyle 1994; Croom & Shanks 1996). However, as reported in Myers et al. (2005) and Ross et al. (2007), the Poisson error under-estimates measurement error when compared to e.g. the field-to-field or Jackknife errors at larger scales, where quasar pairs are not independent. For this work, we will not report any field-to-field errors, but instead concentrate on a jackknife re-sampling procedure in order to calculate the full covariance matrix, from which we will use just the diagonal elements. Full details of the jackknife procedure, including the geometry of the subsamples used and the justification for using only the diagonal elements are given in Section 4 and Appendix B.

## 4. RESULTS

### 4.1. SDSS Quasar Redshift-Space Two-Point Correlation Function, $\xi(s)$ ( $0.30 \leq z \leq 2.2$ )

The two-point redshift-space correlation function for the SDSS DR5Q UNIFORM sample over the redshift interval  $0.3 < z < 2.2$  is given in Figure 3. As described in Appendix B, the errorbars are jackknife errors from the diagonal elements of the covariance matrix, i.e.  $\sigma_i^2 = C_{ii}$ . We justify this approach by considering that the covariance matrix is close to diagonal (Fig. 16) and using just the diagonal elements of the covariance matrix produces results very close to that using the whole matrix, when fitting out to  $25 \, h^{-1} \text{ Mpc}$ . The off-diagonal elements of the covariance matrix are too noisy to be useful at large scales, and we therefore only use the diagonal elements in all the fits and plots that follow.

We start by fitting a simple, single power-law model of the form in Equation 2. We find that a single power law with a redshift-space correlation length of



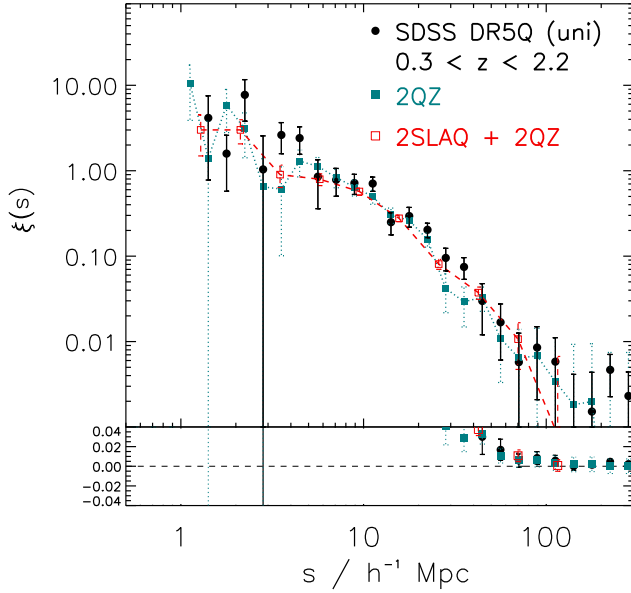


FIG. 4.— The Quasar redshift-space 2PCF,  $\xi(s)$ , from the UNIFORM sample as in Fig. 3. Also shown are the redshift-space correlation functions from the 2QZ (Croom et al. 2005), shown as cerulean filled squares connected with a dotted line, and the 2SLAQ QSO survey (da Ângela et al. 2008), shown as the red filled squares connected by the dashed line. There is excellent agreement between the three surveys.

$s_0 = 5.95 \pm 0.45 \ h^{-1} \text{ Mpc}$  and power-law slope of  $\gamma_s = 1.16^{+0.11}_{-0.08}$  provides an adequate description of the data over the scales  $1.0 \leq s \leq 25.0 \ h^{-1} \text{ Mpc}$  (solid line, Fig. 3). Here a value of  $\chi^2 = 11.5$  is obtained with 11 degrees of freedom (dof) giving  $P$ , the probability of acceptance (of our power law model to the data) of 0.402. A less suitable fit is found at larger scales due to the data falling below the power law. Over the range  $1.0 \leq s \leq 100.0 \ h^{-1} \text{ Mpc}$ , the best fit model has a similar correlation length,  $s_0 = 5.90 \pm 0.30 \ h^{-1} \text{ Mpc}$  but a significantly steeper power-law slope,  $\gamma_s = 1.57^{+0.04}_{-0.05}$  (dotted line, Fig. 3). The  $\chi^2$  for this model is 32.8 with 15 dof and  $P = 5 \times 10^{-3}$ . The data systematically deviate from the power-law fit, possibly due to the effects of redshift-distortions (on small scales), with a “flattening” of the data compared to the model at small,  $s \lesssim 5 \ h^{-1} \text{ Mpc}$ , scales and a steepening at large,  $s \gtrsim 40 \ h^{-1} \text{ Mpc}$ , scales - though a decline below a power-law at large scales is also expected from linear theory via the CDM real-space  $\xi(r)$ .

In Figure 4, we compare our results with the redshift-space correlation function  $\xi(s)$  from two other recent studies, the 2QZ (Croom et al. 2005) and the 2SLAQ QSO (da Ângela et al. 2008) surveys. The analysis by da Ângela et al. (2008) uses data from both the 2QZ and 2SLAQ QSO surveys and thus the samples are not completely independent.

The 2QZ and 2SLAQ QSO surveys both cover very similar redshift ranges to our  $z < 2.2$  sample. The 2QZ covers a much smaller area,  $\approx 750 \text{ deg}^2$ , than the SDSS but has 2/3 as many quasars as our sample, since it reaches to a deeper limiting magnitude of  $b_J = 20.85$  (corresponding to  $g \approx 20.80$  and  $i \approx 20.42$ ). The 2SLAQ QSO survey has a smaller area yet,  $\approx 180 \text{ deg}^2$ , and reaches a magnitude deeper than the 2QZ to  $g = 21.85$

( $i \approx 21.45$ ) resulting in 8 500 quasars with  $0.3 < z < 2.2$ .

The agreement in the correlation function between surveys over  $1 \ h^{-1} \text{ Mpc} \leq s \leq 100 \ h^{-1} \text{ Mpc}$  scales is impressive but not necessarily unexpected, since we are essentially sampling the same type of objects i.e. luminous AGN, powered by supermassive black holes accreting at or near their Eddington limits (Kollmeier et al. 2006; Shen et al. 2008), quite possibly in similar mass environments (see Section 5). However, the samples have different luminosities, with mean  $L_{\text{Bol,SDSS}} = 3.4 \times 10^{46} \text{ erg s}^{-1}$  (Table 2) compared with mean  $L_{\text{Bol,2QZ}} \approx 1.3 \times 10^{46} \text{ erg s}^{-1}$  (assuming  $M_{b_J} = -24.6$  and eqn. 27 from Croom et al. 2005, for the 2QZ QSOs), suggesting that variation in quasar luminosity is due to a variation in SMBH fueling, rather than a variation in SMBH mass (which maybe correlated to halo mass). We explore this luminosity dependence on clustering further in the companion paper (Shen et al. 2009).

Figure 5 displays the very large scale  $\xi(s)$  using the LS estimator. We see that apart from one data point at  $s \approx 400 \ h^{-1} \text{ Mpc}$ , the redshift-space correlation function is within  $1\sigma$  of  $\xi(s) = 0$  at scales greater than  $\sim 300 \ h^{-1} \text{ Mpc}$ . A  $\chi^2$  test comparing the data to  $\xi(s) = 0$  over the range of  $100 \leq s < 1000 \ h^{-1} \text{ Mpc}$  and  $100 \leq s < 3000 \ h^{-1} \text{ Mpc}$  gives  $\chi^2 = 8.2$  (18 dof,  $P = 0.975$ ) and  $\chi^2 = 25.3$  (54 dof,  $P = 0.999$ ), respectively. Our rms scatter is  $\pm 0.001$ , which compares well to the 2QZ value of  $\pm 0.002$ ; with a sample  $\sim 50\%$  larger, we have roughly doubled the pair counts at these very large scales. The dimensions of our sample do not allow us to probe separations beyond  $3000 \ h^{-1} \text{ Mpc}$ .

#### 4.2. SDSS Quasar 2-D 2-Point Correlation Function, $\xi(r_p, \pi)$ ( $0.30 \leq z \leq 2.2$ )

Figure 6 shows the SDSS DR5 Quasar 2-D redshift-space correlation function  $\xi(r_p, \pi)$  for the UNIFORM sample, over  $0.3 \leq z \leq 2.2$ . The redshift-space distortions in the clustering signal - seen as deviations from isotropy - are immediately apparent. At small  $r_p$ , the random peculiar motions and redshift errors of quasars cause an elongation of the clustering signal along the line-of-sight direction,  $\pi$ . This is the well-known “Fingers-of-God” effect (Jackson 1972). Cosmological information can be extracted from the Quasar 2D  $\xi(r_p, \pi)$  measurement (e.g. Hoyle et al. 2002; da Ângela et al. 2005, 2008). However, full treatment of the separation of the effects of large-scale ‘squashing’ in  $r_p$  (used to determine  $\beta(z)$  in equation 12) and the substantial contribution from the Fingers-of-God at small scales is left to a future paper.

#### 4.3. SDSS Quasar Projected 2-Point Correlation Function

In Figure 7, we show the projected 2-point correlation function,  $w_p(r_p)$ , calculated using equation 9. The reported error bars are jackknife errors, using the same jackknife area subsamples as for the  $\xi(s)$  calculation (Appendix B). Since we are fitting power laws of the form  $\xi(r) = (r/r_0)^\gamma$  (equation 10), we plot  $w_p(r_p)/r_p$  on the ordinate. We find the best fitting single power-law to the SDSS Quasar  $w_p(r_p)/r_p$  data to be  $r_0 = 5.45^{+0.35}_{-0.45} \ h^{-1} \text{ Mpc}$  and  $\gamma = 1.90^{+0.04}_{-0.03}$  over our full range of scales,  $0.1 < r_p < 130.0 \ h^{-1} \text{ Mpc}$ . This provides a

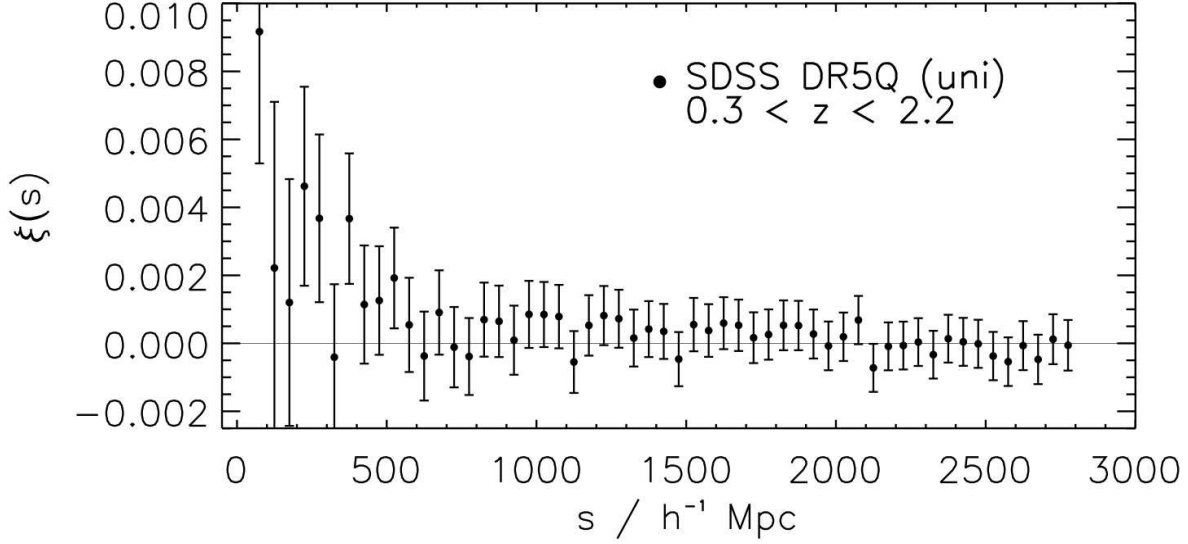


FIG. 5.— The SDSS Quasar redshift-space 2PCF,  $\xi(s)$ , for our UNIFORM sample over the redshift range  $0.3 \leq z \leq 2.2$  at very large scales. Jackknife errors are plotted. The data are consistent with  $\xi(s) = 0$  out to scales of  $s \sim 3000 h^{-1}$  Mpc, which is the largest scales well-sampled by SDSS.

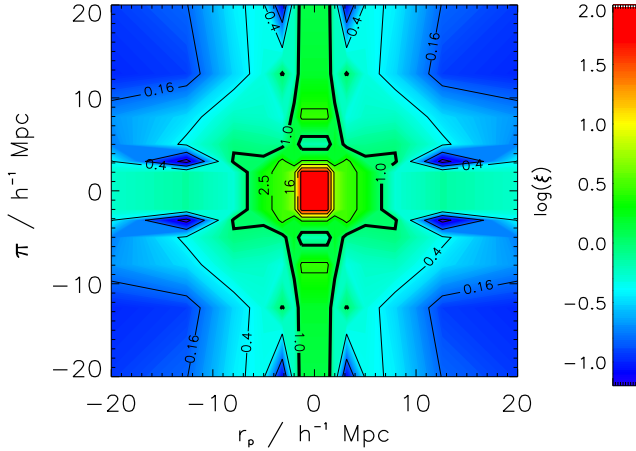


FIG. 6.— The SDSS DR5 Quasar  $\xi(r_p, \pi)$ . The contours give lines of constant  $\xi$  having  $\delta \log \xi = 0.4$  between contours, with  $\log \xi = 1.6$  the highest value at the centre of the plot. The thick contour is  $\xi = 1.0$ . The actual  $\xi(r_p, \pi)$  measurement is repeated and mirrored over four quadrants to show the deviations from circular symmetry.

somewhat poor fit, giving a value of  $\chi^2 = 22.02$  with 12 degrees of freedom ( $P = 0.038$ ). We remind the reader that due to fibre collisions, measurements at scales of  $r_p \lesssim 1 h^{-1}$  Mpc are biased low (Sec. C.6). Restricting the range to  $4.0 < r_p < 130.0 h^{-1}$  Mpc, we find the best fit power-law has an increased real-space correlation length of  $r_0 = 8.75^{+0.35}_{-0.50} h^{-1}$  Mpc and a steeper slope of  $\gamma = 2.40^{+0.07}_{-0.10}$ . This power-law is a more acceptable fit, having  $\chi^2 = 3.47$  with 6 dof ( $P = 0.748$ ). We further suggest that the difference between the fitted results and their dependence on scale is due to a “break” in the  $w_p(r_p)/r_p$  measurements at  $r_p \sim 2 - 5 h^{-1}$  Mpc. However, we are hesitant to offer an explanation of this behaviour of our measurements in terms of, e.g. the transition from the 1 to 2-halo regime (cf. Porciani et al. 2004).

Comparisons of our  $w_p(r_p)/r_p$  results to those of Shen et al. (2007) for the  $z > 2.9$  redshift quasar measurements shows that the high redshift SDSS quasars

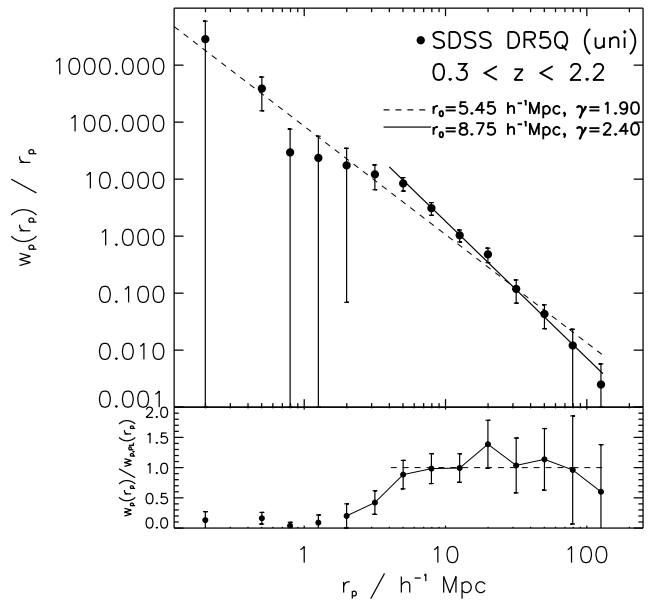


FIG. 7.— The SDSS Quasar redshift-space 2PCF,  $w_p(r_p)$ . The dashed line shows the best fit single power law to the data over our full range of scales,  $0.1 < r_p < 130.0 h^{-1}$  Mpc. Here, the real-space correlation length is  $r_0 = 5.45^{+0.35}_{-0.45} h^{-1}$  Mpc with a slope  $\gamma = 1.90^{+0.04}_{-0.03}$ . Restricting the range to  $4.0 < r_p < 130.0 h^{-1}$  Mpc, the best-fit values become  $r_0 = 8.75^{+0.35}_{-0.50} h^{-1}$  Mpc and  $\gamma = 2.40^{+0.07}_{-0.10}$ . The lower panel shows the ratio of the data divided by the power-law model over  $4.0 < r_p < 130.0 h^{-1}$  Mpc.

have a much larger clustering amplitude than the lower redshift sample. The consequences of this are discussed in detail in Shen et al. (2007).

#### 4.4. Evolution of the SDSS Quasar Correlation Function

Figures 8 and 9 present the evolution of the redshift-space,  $\xi(s)$ , and the projected,  $w_p(r_p)$ , 2PCF, using the SDSS DR5 UNIFORM Quasar sample.

We plot both  $\xi(s)$  and  $w_p(r_p)$  for sub-samples of the UNIFORM data, with the relevant redshift limits given



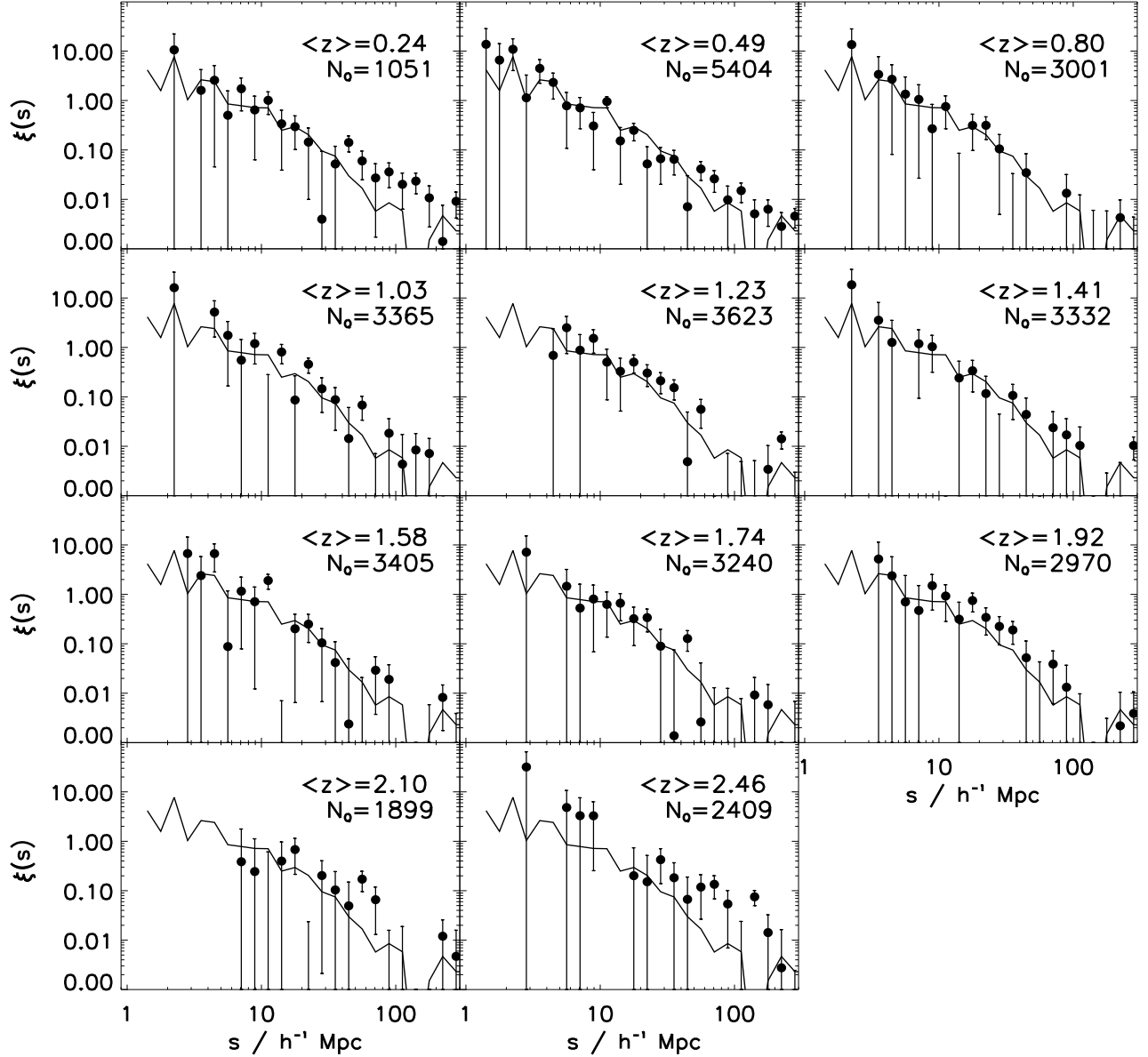


FIG. 8.— The SDSS DR5 Quasar redshift-space 2PCF,  $\xi(s)$ , and its evolution with redshift. All panels have the same scaling with the respective number of quasars,  $N_Q$ , in each redshift range given. The thin (black) line in each panel is  $\xi(s)$  for the full DR5Q UNIFORM sample, over  $0.30 < z < 2.20$ . The quoted errorbars are Poisson (see text for justification).

in Table 2. Here we choose the redshift slices so that we match those of the 2QZ Survey given by Croom et al. (2005). Our survey generally has 50% more data in each redshift bin. However, since the 2QZ selects QSO candidates on the basis of their stellar appearance on photographic plates, low-redshift quasars with detectable host galaxies on the plate are preferentially rejected from the final 2QZ catalogue, and the SDSS Quasar UNIFORM sample has a larger proportion of low,  $z \lesssim 0.5$ , redshift quasars<sup>8</sup>. We fit power-law models of the form given by

<sup>8</sup> The larger number of low redshift quasars in the SDSS sample is also at least in part due to the contribution of the H $\alpha$  emission line in the  $i$ -band, as well as host galaxy contribution at low redshift.

equation (2), over the ranges  $1.0 \leq s \leq 25.0 \ h^{-1} \text{ Mpc}$  (except for our  $2.02 \leq z < 2.20$  bin, where to get finite constraints, we fit to  $s_{\text{max}} = 100 \ h^{-1} \text{ Mpc}$ ). The best fit parameters and corresponding  $1\sigma$  errors are given in Table 2.

In Fig. 8, we show measurements for  $\xi(s)$  for the redshift slices. The measurement of  $\xi(s)$  for the full redshift range measurement is given by the thin line in each panel. We show Poisson errors as these are approximately equal to jackknife errors on scales where the number of  $DD$  pairs is less than the number of quasars in the (sub)sample (see Fig. 17 and Appendix B). This scale is  $s \sim 40 - 80 \ h^{-1} \text{ Mpc}$  for the sub-samples given here. As such, the errorbars on scales  $\gtrsim 80 \ h^{-1} \text{ Mpc}$  are

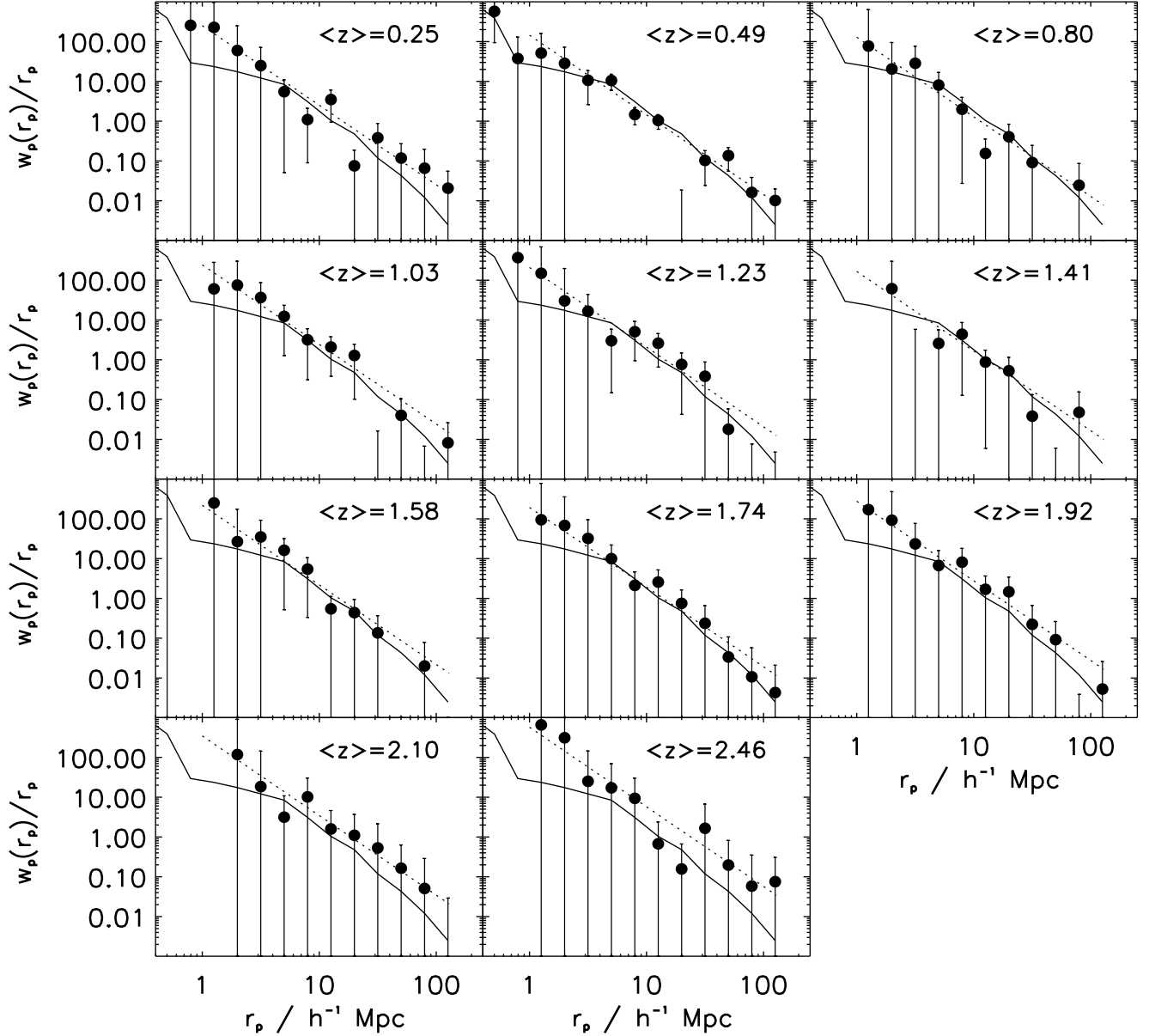


FIG. 9.— The SDSS DR5 Quasar projected 2PCF,  $w_p(r_p)$ , and its evolution with redshift. The solid line in each panel is  $w_p(r_p)/r_p$  for the full DR5Q UNIFORM sample, over  $0.30 < z < 2.20$ . The quoted errorbars are scaled jackknives (see text for details). The relevant power-law fits as given in Table 2 are shown by the dotted lines.

most likely under-representative. The  $\xi(s)$  data show a trend to ‘lose’ quasar-quasar  $DD$  pairs at the smallest separation, as the redshift increases. Keep in mind that the length scale suppressed due to the 55” fibre collision limitation increases from  $s \sim 0.2 h^{-1}$  Mpc at  $z = 0.5$  to  $s \sim 1 h^{-1}$  Mpc at  $z = 2$  (Fig. 23), giving rise to the apparent depression in the correlation function on small scales.

Fig. 9 ( $w_p(r_p)/r_p$ ) has the same format as Fig. 8. However, here we show scaled jackknife errors, scaled using the  $w_p(r_p)/r_p$  Poisson and Jackknife error measurements from the full sample. As can be seen from inspection, the errorbars plotted here have generally larger magnitudes than the spread of the data alone. As such, this leads to

questioning whether this is due to the Poisson errors being general under-estimates or the jackknives being over-estimates of the true error<sup>9</sup>.

As a check, we calculate the “summed variance” Poisson errors, that is, we sum the variances of each bin included in the integral for  $w_p(r_p)$ . This method returns smaller errors than those shown in Fig. 9, especially at the smaller,  $r_p < 10 h^{-1}$  Mpc, scales. Re-assuringly, when we come to fit single power-law models for  $\xi(r)$  (Sec. 5.2) in order to find values for the real-space correlation length,  $r_0$ , the best-fit values we find from

<sup>9</sup> The interested reader is pointed towards recent work by Norberg et al. (2008), who use large  $N$ -body simulations to investigate different error estimators and the 2PCF for galaxy clustering.

TABLE 2  
EVOLUTION OF THE REAL-SPACE CORRELATION LENGTH

$z$ -interval	$\bar{z}$	$N_q$	$L_{\text{Bol}}$ ( $10^{46}$ erg s $^{-1}$ )	$s_0 / h^{-1}$ Mpc	$\gamma_s$	$\chi^2$	$\nu$	$s_0 / h^{-1}$ Mpc ( $\gamma_s = 1.16$ )	$r_0 / h^{-1}$ Mpc ( $\gamma = 2.0$ )
0.30,2.20	1.269	30 239	3.43	$5.95 \pm 0.45$ $^a 5.90 \pm 0.30$	$1.16^{+0.11}_{-0.16}$ $1.57^{+0.04}_{-0.05}$	11.5 32.8	11 17	$5.95 \pm 0.45$	$5.45^{+0.35}_{-0.45}, \gamma = 1.90^{+0.04}_{-0.03}$ $8.75^{+0.35}_{-0.50}, \gamma = 2.40^{+0.07}_{-0.10}$
0.08,0.30	0.235	1 051	0.16	$6.90^{+1.35}_{-1.50}$	$1.37^{+0.41}_{-0.31}$	2.6	9	$6.20 \pm 1.55$	$8.95 \pm 0.92$
0.30,0.68	0.488	5 404	0.50	$6.05^{+0.45}_{-0.65}$	$1.67^{+0.23}_{-0.24}$	12.2	11	$4.60^{+0.80}_{-0.75}$	$6.78 \pm 0.56$
0.68,0.92	0.801	3 001	1.39	$7.05^{+1.15}_{-1.45}$	$1.90^{+0.60}_{-0.60}$	6.2	8	$5.40^{+1.60}_{-1.70}$	$6.40 \pm 0.64$
0.92,1.13	1.029	3 365	2.07	$2.68^{+1.42}_{-1.28}$	$0.57^{+0.14}_{-0.15}$	9.4	7	$6.30^{+1.60}_{-1.65}$	$8.80 \pm 0.84$
1.13,1.32	1.228	3 623	2.83	$7.10^{+1.45}_{-1.65}$	$1.00^{+0.30}_{-0.25}$	2.5	6	$7.75^{+1.50}_{-1.60}$	$8.14 \pm 0.92$
1.32,1.50	1.412	3 332	3.60	$6.05^{+1.35}_{-1.85}$	$2.13^{+0.87}_{-0.78}$	6.1	7	$3.65^{+1.70}_{-1.85}$	$7.26 \pm 0.93$
1.50,1.66	1.577	3 405	4.40	$6.10^{+1.60}_{-1.70}$	$1.67^{+0.81}_{-0.50}$	13.5	8	$4.65^{+1.80}_{-1.70}$	$8.34 \pm 0.84$
1.66,1.83	1.744	3 240	5.29	$7.70^{+1.70}_{-1.90}$	$1.11^{+0.39}_{-0.31}$	1.0	6	$7.90^{+1.80}_{-1.85}$	$7.83 \pm 0.71$
1.83,2.02	1.917	2 970	6.63	$7.43^{+2.37}_{-2.43}$	$0.84^{+0.41}_{-0.30}$	2.5	7	$8.70^{+2.05}_{-2.15}$	$9.38 \pm 0.79$
2.02,2.20	2.104	1 899	8.69	$^a 3.65^{+1.60}_{-1.85}$	$1.10^{+0.29}_{-0.15}$	8.7	10	$4.10^{+1.75}_{-1.90}$	$10.50 \pm 0.96$
2.20,2.90	2.462	2 409	11.64	$10.75^{+2.15}_{-3.42}$	$2.60^{+0.60}_{-1.10}$	0.2	4	$7.15^{+1.90}_{-6.45}$	$13.51 \pm 1.81$

NOTE. — Evolution of the redshift-space,  $s_0$ , and real-space,  $r_0$ , correlation lengths. For  $s_0$ , both the correlation length and power-law slope were allowed to vary. All redshift-space subsamples were fitted over the range  $1.0 \leq s \leq 25.0 h^{-1}$  Mpc, unless otherwise noted with  $^a$ , where the range was  $1.0 \leq s \leq 100.0 h^{-1}$  Mpc. For  $s_0$  we quote values both with floating and fixed ( $\gamma_s = 1.16$ ) power-laws. For the full sample,  $r_0$  and  $\gamma$  are allowed to vary and fits were performed over the scales  $1.0 \leq r_p \leq 130.0 h^{-1}$  Mpc. While for the real-space subsamples, the calculation of  $r_0$  was made by fitting our wp(rp)/rp measurements using equation 10, over the  $1.0 \leq r_p \leq 130.0 h^{-1}$  Mpc, while keeping the power-law index fixed at  $\gamma = 2.0$ . The bolometric luminosities are from the catalogue of Shen et al. (2008).

using the “summed variance” errors are in good agreement with those found using our  $w_p(r_p)/r_p$  “averaging” method quoted in Table 2. We explicitly note though that there still could be an issue with the jackknife errors being too large (for  $w_p(r_p)/r_p$ ) currently for reasons unknown.

Figure 10 shows the evolution of the redshift-space correlation length,  $s_0$ , with both redshift and the age of the Universe (adopting the cosmology given at the end of Section 1). Since there is a covariance between the best-fit  $s_0$  and  $\gamma_s$ , here we fix  $\gamma_s$  to the best-fit value of the whole sample ( $\gamma_s = 1.16$ ) and then measure the best-fit  $s_0$ . We find the clustering strength remains reasonably constant with redshift out to  $z \sim 3$ , which is equivalent to approximately 80% of the history of the Universe. This trend was also seen in Fig. 8. The correlation length is measured to be  $s_0 = 5 - 7 h^{-1}$  Mpc for bright, optically identified quasars in the SDSS, up to  $z \sim 3$ .

## 5. EVOLUTION OF GALAXY, AGN AND QUASAR CLUSTERING

### 5.1. The Redshift-Space Evolution

In Figure 10, we compare our measurements of the evolution of the redshift-space correlation length,  $s_0$ , to those recently published in the literature. We calculate our values for  $s_0$  by fitting our  $\xi(s)$  measurements using equation 2. Motivated by the fits in Fig. 3, we hold the power-law index fixed at  $\gamma_s = 1.16$ . The study of quasar clustering most comparable to our own is that presented by Croom et al. (2005) for the 2QZ survey. Our study using the SDSS DR5Q UNIFORM quasar sample and the 2QZ are in very good agreement over the full redshift range, given the associated uncertainties. However, in the SDSS DR5Q sample, we see very little, if any, evolution in the redshift-space correlation length even to  $z \sim 3$ , whereas the 2QZ does show marginal evolution in  $s_0$ . The similarity of these results again suggests that quasar clustering only weakly depends on luminosity for

the dynamical ranges probed in these samples, a topic discussed further in Shen et al. (2009).

The filled (red) star in Fig. 10 is from the study by Wake et al. (2004) who use a sample of 13 605 narrow-line AGNs in the redshift range  $0.055 < z < 0.2$  from the first Data Release of the SDSS (Abazajian et al. 2003). They find that the AGN autocorrelation function is consistent with the observed galaxy autocorrelation function over  $s = 0.2 - 100 h^{-1}$  Mpc scales. Furthermore, they show that the AGN 2PCF is dependent on the luminosity of the narrow [O III] emission line ( $L_{[\text{OIII}]}$ ), with low  $L_{[\text{OIII}]}$  AGNs having a higher clustering amplitude than high  $L_{[\text{OIII}]}$  AGNs. This measurement suggests that lower activity AGNs reside in more massive DM haloes than do higher activity AGNs, as  $L_{[\text{OIII}]}$  provides a good indicator of AGN fueling rate (e.g. Miller et al. 2003; Kauffmann et al. 2003). As such, it is interesting to note that our lowest redshift quasar clustering data point is, within the uncertainties, consistent with the measurement from Wake et al. (2004). We use the term ‘quasar’ here loosely, as for our lowest redshift bin, the mean bolometric luminosity is  $1.6 \times 10^{45}$  ergs s $^{-1}$ , a factor of 20 lower than our full sample (Table 2).

Constantin & Vogeley (2006) study the clustering of specific classes of AGN, namely Seyfert galaxies and LINERs (low-ionization nuclear emission-line regions) with the classes being separated on the basis of emission-line diagnostic diagrams (e.g. Baldwin et al. 1981; Kewley et al. 2001). They find that LINERs, which show the lowest luminosities and obscuration levels, exhibit strong clustering ( $s_0 = 7.82 \pm 0.64 h^{-1}$  Mpc), suggesting that these objects reside in massive haloes and thus presumably have relatively massive black holes that are weakly active or inefficient in their accretion, potentially due to the insufficiency of their fuel supply. Seyfert galaxies, however, have lower clustering,  $s_0 = 5.67 \pm 0.62 h^{-1}$  Mpc (Fig. 10, blue triangle), are very luminous and show large emitting gas densities, suggest-

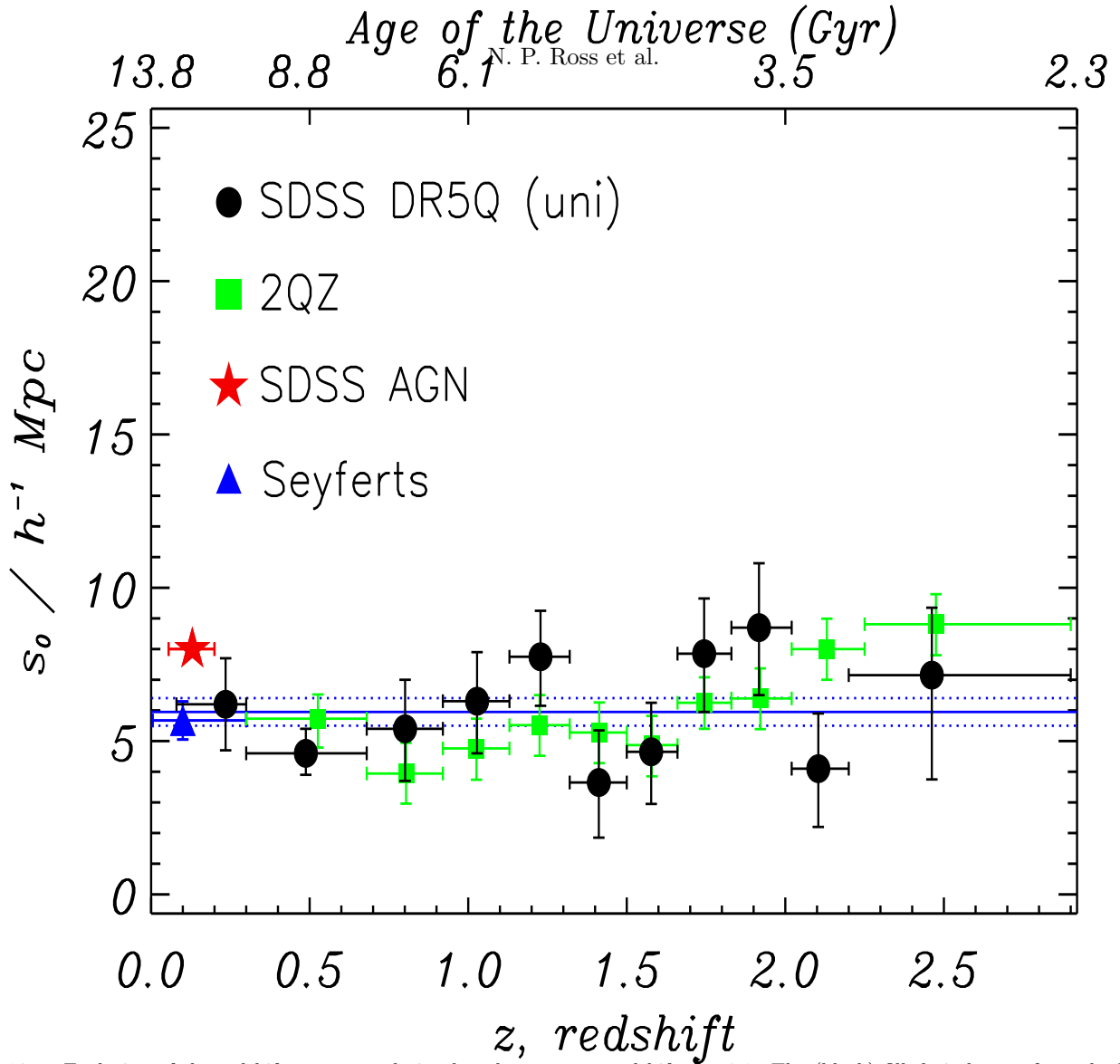


FIG. 10.— Evolution of the redshift-space correlation length,  $s_0$ , up to redshift  $z = 2.9$ . The (black) filled circles are from the DR5Q UNIFORM sample and the (blue) line gives the best-fit value for the whole sample with associated  $1\sigma$  errors. The (green) filled squares are from the 2QZ (Croom et al. 2005), while the (red) filled star is from a measurement of AGN clustering at  $z < 0.2$  by Wake et al. (2004). The (blue) filled triangle is the clustering measurement of Seyfert galaxies from Constantin & Vogeley (2006).

ing that their black holes are less massive but accrete quickly and efficiently enough to dominate the ionization. Therefore, based on our lowest redshift clustering results, the stronger link for our low-luminosity ‘quasars’ is to Seyfert galaxies rather than LINERs.

### 5.2. The Real-Space Evolution

In Figure 11, we compare our measurements (black circles) of the evolution of the real-space correlation length,  $r_0$ , to those recently published in the literature. We calculate our values for  $r_0$  by fitting our  $w_p(r_p)/r_p$  measurements using equation 10, calculating an  $r_0$  value at each separation where  $w_p(r_p)/r_p$  is non-zero, and reporting the standard error on the mean for these values in Table 2. Motivated by the fits in Fig. 7, we hold the power-law index fixed at  $\gamma = 2.0$ , thus setting  $A(\gamma = 2) = \pi$  (eqn. 10). We caution again however, that as can be seen from inspecting Fig. 9, the scatter in the points is small compared to the quoted errorbars, and thus, this method may well under-estimate the errors associated with the real-space correlation length.

Myers et al. (2006) reported a measurement of the clustering of quasars using  $\sim 80\,000$  SDSS

quasars photometrically classified from the catalogue of Richards et al. (2004). The  $r_0$  measurements from Myers et al. (2006) are given by the filled (red) squares in Fig. 11, and are in very good agreement with our own data (we plot the data from their Table 1, from the ‘De-projected  $r_0$ ’ section and the  $0.75 \leq r < 89\,h^{-1}$  Mpc row).

Coil et al. (2007) calculate the cross-correlation between  $\sim 30\,000$  redshift  $0.7 < z < 1.4$  galaxies observed as part of the DEEP2 galaxy redshift survey (Davis et al. 2001, 2003), and quasars over the same redshift range. In total there are 36 SDSS quasars and 16 quasars identified from the DEEP2 survey itself over the  $3\,\text{deg}^2$  covered by the DEEP2. Coil et al. (2007) find that  $r_0 \sim 3.4 \pm 0.7\,h^{-1}$  Mpc for the quasar-galaxy cross-correlation ( $\xi_{QG}$ ). These authors measure  $r_0 \sim 3.1 \pm 0.6\,h^{-1}$  Mpc for the inferred quasar clustering scale length, assuming that  $\gamma$  is the same for the galaxy and the quasar samples and the two samples trace each other perfectly, giving  $\xi_{QG} = \sqrt{\xi_{QQ} \times \xi_{GG}}$ . We show this measurement as an open (purple) diamond in Fig. 11. Although still consistent with the low-redshift measurement of Myers et al.

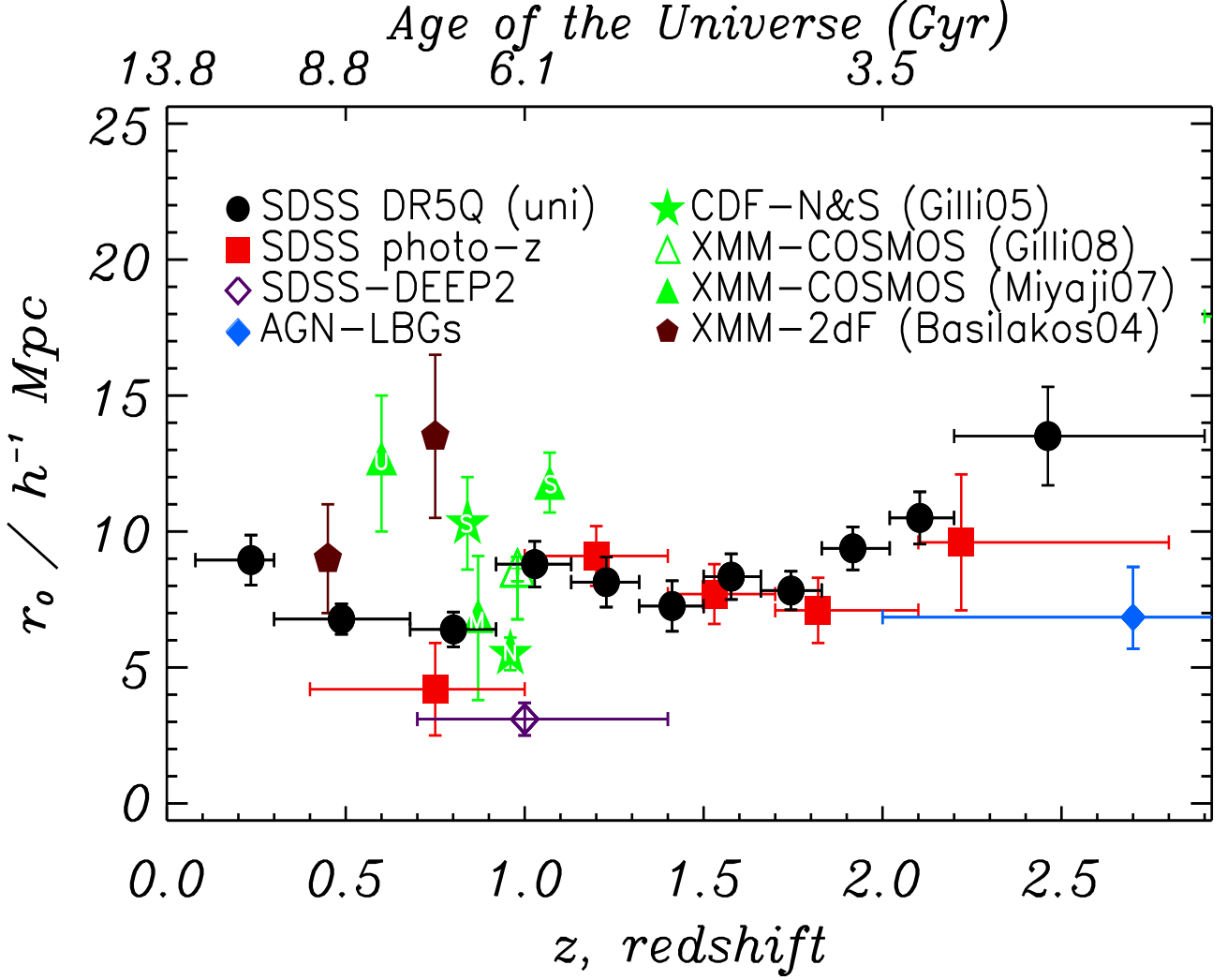


FIG. 11.— Evolution of the real-space correlation length,  $r_0$ , up to redshift  $z = 2.9$ . The filled (black) circles are from the DR5Q UNIFORM sample (this work); the filled (red) squares are from the photometric sample of SDSS quasars from Myers et al. (2006); The open (purple) diamond is the quasar-galaxy cross-correlation from the DEEP2 Survey (Coil et al. 2007) and the solid (blue) diamond is the AGN-galaxy cross-correlation using Lyman Break galaxies (LBGs, Adelberger & Steidel 2005b). X-ray data from the *Chandra* Deep Fields (Gilli et al. 2005) are shown by filled (green) 5-pointed stars (with the North and South fields denoted ‘N’ and ‘S’ respectively); the *XMM-Newton*-2dF survey (Basilakos et al. 2004) are indicated by filled (dark red) pentagons; the *XMM-Newton* COSMOS survey (Miyaji et al. 2007), is shown by filled (green) triangles, with the ‘SFT’ (0.5–2 keV), ‘MED’ (2–4.5 keV) and ‘UHD’ (4.5–10 keV) band measurements denoted as S, M and U respectively. Measurements from Gilli et al. (2008), also using the *XMM-Newton* COSMOS survey, are given by the open (green) triangle.

(2006), it is at odds with our measurements. Determination of  $\xi_{QQ}$  from the cross-correlation measurement assumes that the density fields traced by the galaxies and quasars,  $\delta_G$  and  $\delta_Q$  respectively, are perfectly correlated spatially, i.e. the correlation coefficient between the two is  $r = +1$  (e.g. Blanton et al. 1999; Swanson et al. 2008)<sup>10</sup>. Thus, as is quite plausible, if  $z \sim 1$  quasars and galaxies sample the underlying mass density field differently, then one can reconcile the difference in correlation lengths by invoking a correlation coefficient that is modestly different from unity.

Adelberger & Steidel (2005a,b) studied the clustering of Lyman Break galaxies (LBGs) around  $2 \lesssim z \lesssim 3$  AGN. The dynamic range in luminosity for this sample is nearly

<sup>10</sup> The simplest and frequently assumed relationship between  $\delta_1$  and  $\delta_2$  is “deterministic linear bias”,  $\delta_1 = b_{\text{lin}} \delta_2$  where  $b_{\text{lin}}$  is a constant parameter,  $\delta_1 = \rho_1(\mathbf{x})/\bar{\rho}_1 - 1$  and  $\delta_2 = \rho_2(\mathbf{x})/\bar{\rho}_2 - 1$ , e.g. Peebles (1980); Dekel & Lahav (1999); Swanson et al. (2008).

10 magnitudes ( $16 \lesssim G_{\text{AB}} \lesssim 26$ , Adelberger & Steidel 2005b) and is thus much greater than for our SDSS DR5 UNIFORM sample. These authors report a value of  $r_0 = 5.27^{+1.59}_{-1.36} h^{-1} \text{ Mpc}$  for a sample of 38 AGN with central SMBH masses of  $10^{5.8} < M_{\text{BH}}/M_{\odot} < 10^8$  and  $r_0 = 5.20^{+1.85}_{-1.16} h^{-1} \text{ Mpc}$  for a sample of 41 AGN with  $10^8 < M_{\text{BH}}/M_{\odot} < 10^{10.5}$ . If we assume the correlation coefficient is  $r = 1$  and the power-law slopes are constant between samples, we find (with  $r_{0,\text{LBG-LBG}} = 4.0 \pm 0.6 h^{-1} \text{ Mpc}$  at  $z = 2.9$ , Adelberger et al. 2005) that  $r_{0,\text{AGN-AGN}} \approx 6.9 h^{-1} \text{ Mpc}$ . This result is very broadly consistent with Myers et al. (2006) but in tension with our SDSS DR5 UNIFORM results. Adelberger & Steidel (2005b) sample vastly different luminosity ranges than we do and find the clustering does not vary significantly with luminosity, immediately ruling out luminosity dependence as an explanation of the different clustering amplitudes. Again, the assumption of perfect correla-



tion is called into question, with a non-unity correlation coefficient  $r$  potentially reconciling both these and the Coil et al. (2007) DEEP2 results.

We also compare our results with clustering measurements of recent deep X-ray surveys, which are particularly well suited to finding intrinsically less luminous, potentially obscured objects at high redshift (Brandt & Hasinger 2005). An immediate caveat we place in the following comparison is that the SDSS DR5Q surveys  $\sim 4000 \text{ deg}^2$ , while the largest solid angle of the current deep X-ray surveys is of order  $1 \text{ deg}^2$  and therefore the X-ray results are much more susceptible to cosmic variance.

Basilakos et al. (2004) estimate  $r_0$  using the angular autocorrelation function,  $w(\theta)$ , of hard, (2-8 keV) X-ray selected sources detected in a  $\approx 2 \text{ deg}^2$  field using a shallow ( $f_X[2-8 \text{ keV}] \approx 10^{-14} \text{ ergs cm}^{-2} \text{ s}^{-1}$ ) and contiguous *XMM-Newton* survey. The area surveyed consisted of 13 usable pointings, overlapping that of the 2QZ survey, and resulted in the detection of 171 sources. Various models for the redshift distribution are given in Basilakos et al. (2004, see their Table 1); for our comparison, we adopt the  $r_0$  values calculated using  $(\Omega_m, \Omega_\Lambda) = (0.3, 0.7)$ , which either assume “pure luminosity evolution” (PLE, Boyle et al. 1998) or “luminosity-dependent density evolution” (LDDE, Ueda et al. 2003). As such, the PLE and LDDE models produce different mean redshifts of  $\bar{z} = 0.45$  and  $\bar{z} = 0.75$ , respectively, for the AGN sample. Basilakos et al. (2004) find  $r_0 = 9.0 \pm 2.0 h^{-1} \text{ Mpc}$  for the PLE model and  $r_0 = 13.5 \pm 3 h^{-1} \text{ Mpc}$  for the LDDE model, fixing the power-law slope at  $\gamma = 2.2$ . These observations are given by filled (dark red) pentagons in Fig. 11.

Gilli et al. (2005) obtained a sample of nearly 260 AGN in the *Chandra* Deep Field North (CDF-N, Alexander et al. 2003; Barger et al. 2003) and South (CDF-S, Rosati et al. 2002) with spectroscopic redshifts. They report that in both fields the AGN have  $\bar{z} \sim 0.9$  and a median 0.5-10 keV luminosity of  $\bar{L}_X \sim 10^{43} \text{ erg s}^{-1}$ , i.e. in the local Seyfert galaxy luminosity regime. Correlation lengths and slopes of  $r_0 = 5.5 \pm 0.6 h^{-1} \text{ Mpc}$ ,  $\gamma = 1.50 \pm 0.12$  and  $r_0 = 10.3 \pm 1.7 h^{-1} \text{ Mpc}$ ,  $\gamma = 5.5 \pm 0.6$  are found for the CDF-N and CDF-S respectively (Gilli et al. 2005, their Table 2), shown as filled (green) stars in Fig. 11.

Miyaji et al. (2007) measured the angular autocorrelation function of X-ray point sources detected by *XMM-Newton* in the  $\sim 2 \text{ deg}^2$  COSMOS field (Scoville et al. 2007). The measurements for the 0.5-2 (SFT), 2-4.5 (MED) and 4.5-10 (UHD) keV bands are given by filled (green) triangles in Fig. 11. Gilli et al. (2008) also report on the spatial clustering of AGN in the COSMOS field using  $\sim 550$  spectroscopically identified AGN at a median redshift and 0.5-10 keV luminosity of  $z = 0.98$  and  $L_X = 6.3 \times 10^{43} \text{ erg s}^{-1}$  respectively. They find a value of  $r_0 = 8.65 \pm 0.5 h^{-1} \text{ Mpc}$  (Fig. 11, open green triangle) and a power-law slope of  $\gamma = 1.88 \pm 0.07$ . However, this result is affected by a coherent structure of 40 AGN at  $z \sim 0.36$ . Removing this structure causes  $r_0$  to drop to  $\sim 6 h^{-1} \text{ Mpc}$ , similar to that of the previous deep X-ray AGN measurements.

We find that our clustering measurements are in good agreement with the lower correlation lengths found by some of the deep X-ray surveys, e.g. Gilli et al. (2005)

TABLE 3

$\langle z \rangle$	$\bar{\xi}_Q(s, z)$	$\bar{\xi}_\rho(r, z)$	$b$
1.27	$0.391 \pm 0.011$	0.069	$2.06 \pm 0.03$
0.24	$0.462 \pm 0.104$	0.176	$1.41 \pm 0.18$
0.49	$0.363 \pm 0.028$	0.138	$1.38 \pm 0.06$
0.80	$0.311 \pm 0.133$	0.104	$1.45 \pm 0.38$
1.03	$0.383 \pm 0.118$	0.085	$1.83 \pm 0.33$
1.23	$0.524 \pm 0.095$	0.072	$2.37 \pm 0.25$
1.41	$0.309 \pm 0.134$	0.062	$1.92 \pm 0.50$
1.58	$0.411 \pm 0.119$	0.054	$2.42 \pm 0.40$
1.74	$0.472 \pm 0.141$	0.049	$2.79 \pm 0.47$
1.92	$0.674 \pm 0.166$	0.043	$3.62 \pm 0.49$
2.10	$0.425 \pm 0.442$	0.039	$2.99 \pm 1.42$

NOTE. — The evolution of the linear bias for the SDSS Quasar UNIFORM sample.

for the CDF-N, Miyaji et al. (2007) for their MED (2-4.5 keV) band and XMM-COSMOS (Gilli et al. 2008). However, there remains much scatter in the deep X-ray data, potentially due to cosmic variance and the small samples used for these analyses. Thus, we use the method given by Somerville et al. (2004) to estimate the “relative cosmic variance”,  $\sigma_v^2 \equiv \frac{\langle N^2 \rangle - \langle N \rangle^2}{\langle N \rangle^2} - \frac{1}{\langle N \rangle}$ , where  $\langle N \rangle$  is the mean and  $\langle N^2 \rangle$  the variance of the probability distribution function  $P_N(V)$ , which represents the probability of counting  $N$  objects in volume  $V$ . The second term here is the correction for Poisson shot noise. For the XMM-COSMOS study by Gilli et al. (2008) we assume that the COSMOS area is  $2 \text{ deg}^2$  and therefore the volume is  $\sim a \text{ few } \times 10^7 h^{-1} \text{ Mpc}$  (from Fig. 1 in Scoville et al. 2007). We also assume a number density of  $1.8 \times 10^{-4} h^3 \text{ Mpc}^{-3}$  Gilli et al. (2008, Fig. 9) for the COSMOS-XMM AGN, and a redshift of  $z = 1$ , even though the range is known to be much wider. This gives a bias of  $b \sim 2.2$  according to Fig. 3 of Somerville et al. (2004). (Interestingly, this is very much in line with what we find in the next section for the SDSS quasars at this redshift). Thus, the  $\sigma_{v, \text{COSMOS}}^2 \approx 4 \times 10^{-3}$ , which suggests that the COSMOS survey shouldn’t be dominated by cosmic variance. However, we note that this value does not take into account the Poisson shot noise term,  $1/\langle N \rangle$ , which is likely to be significant considering the relatively small number ( $\sim 500$ ) of objects in the XMM-COSMOS sample. For the Chandra Deep Fields, the cosmic variance is much greater due to the fact that the areas are (at least) an order of magnitude smaller. (CDF-N is  $0.13 \text{ deg}^2$ ; CDF-S is  $0.04 \text{ deg}^2$ ). This could well explain the difference between the two CDF clustering measurements (as has been discussed in the relevant studies). We also note that the AGN-LBG study comes from an area of  $\sim 0.5 \text{ deg}^2$  (Steidel et al. 2004) and so cosmic variance could potentially be an explanation for the difference seen in Fig. 11.

### 5.3. Evolution of Bias

One key reason for measuring the correlation function as a function of redshift,  $\xi(s, z)$ , is to determine the linear bias,  $b$ , defined by the model of equation (1). We shall assume that  $b$  is independent of scale on the scales and redshift range under investigation here.<sup>11</sup> We follow

<sup>11</sup> The precise way in which galaxies/luminous AGN trace the underlying matter distribution is still poorly understood.

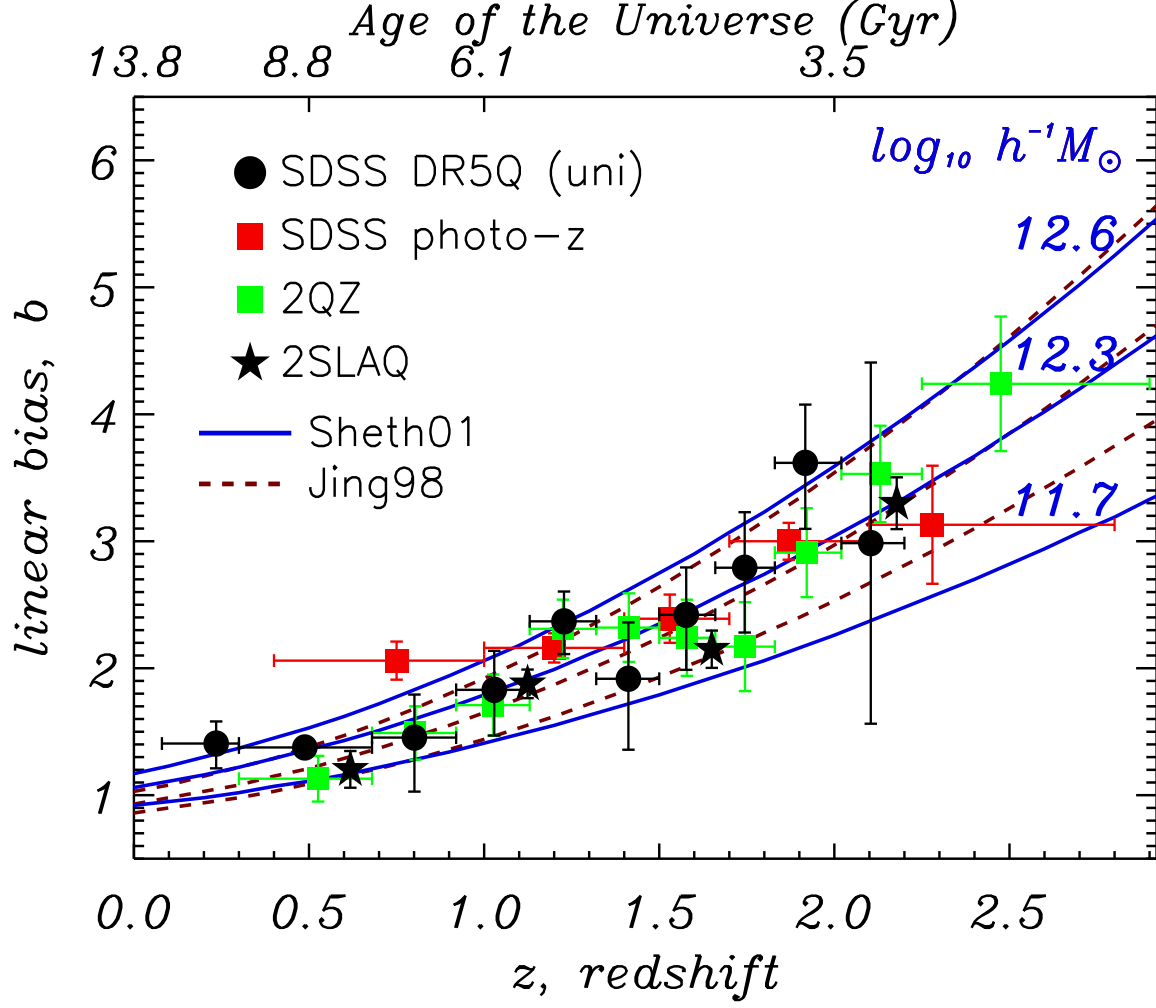


FIG. 12.— Evolution of the linear bias of quasars,  $b_Q$ , with redshift, to  $z = 3$ . The (black) circles, are from the SDSS DR5Q UNIFORM sample (this work); the (red) squares, from the photometric SDSS quasar measurements (Myers et al. 2006); the (green) squares from the 2QZ survey (Croom et al. 2005); the (black) stars are from the 2SLAQ QSO survey (da Ângela et al. 2008); The solid lines give dark halo masses from the models of Sheth et al. (2001) with  $\log h^{-1} M_\odot = 12.6, 12.3$  and  $11.7$  from top to bottom. The dotted lines give dark halo masses from the models of Jing (1998) with  $\log h^{-1} M_\odot = 12.3, 12.0$  and  $11.7$  from top to bottom.

the method in Croom et al. (2005) and da Ângela et al. (2008) to determine  $b$  using our redshift-space correlation function  $\xi(s, z)$  measurements from Section 4.

In order to minimize non-linear effects e.g. redshift-space distortions, we shall use the volume-averaged correlation function,  $\bar{\xi}$ , defined as

$$\bar{\xi} = \frac{\int_{s_{\min}}^{s_{\max}} 4\pi s'^2 \xi(s') ds'}{\int_{s_{\min}}^{s_{\max}} 4\pi s'^2 ds'} \quad (14)$$

$$= \frac{3}{(s_{\max}^3 - s_{\min}^3)} \int_{s_{\min}}^{s_{\max}} \xi(s') s'^2 ds'. \quad (15)$$

where  $s_{\min} = 1.0 h^{-1}$  Mpc is set in practice. Unless explicitly stated otherwise,  $s_{\max}$  is always chosen to be  $20 h^{-1}$  Mpc, so that non-linear effects in the sample should be small due to the  $s^2$  weighting and for ease of comparison with Croom et al. (2005) and

Blanton et al. (2006), Schulz & White (2006), Smith et al. (2007) and Coles & Erdogdu (2007) all suggest that bias is potentially scale dependent. We do not take this into account in the current analysis.

da Ângela et al. (2008). In the linear regime, the  $z$ -space and real-space correlation functions can be given by equation (11). Thus we combine equations (1) and (11), and recognise that  $\beta = \Omega_m^{0.55}/b$  leaves us with a quadratic equation in  $b$ . We are assuming a flat, cosmological-constant model and hence the effective exponent of  $\Omega_m$  is 0.55 (Linder 2005; Guzzo et al. 2008) rather than 0.6, suggested by Peebles (1980), although we find this makes virtually no difference to our bias measurements. Solving the quadratic in  $b$  leads to

$$b(z) = \sqrt{\frac{\bar{\xi}_Q(s, z)}{\bar{\xi}_\rho(r, z)} - \frac{4\Omega_m^{1.1}(z)}{45} - \frac{\Omega_m^{0.55}(z)}{3}}. \quad (16)$$

We now use our measured  $\bar{\xi}_Q(s, z)$  together with a theoretical estimate of  $\bar{\xi}_\rho(r, z)$  and  $\Omega_m(z)$  to determine the bias.

To estimate  $\bar{\xi}_\rho(r, z)$ , we follow Myers et al. (2007) and da Ângela et al. (2008), and use the non-linear estimate of  $P(k)$  given by Smith et al. (2003). The models of Smith et al. (2003) predict the non-linear power spectrum of dark matter for a range of CDM cosmologies over

a wide range of scale. We thus Fourier transform these  $P(k)$  models and integrate over  $s = 1 - 20 h^{-1}$  Mpc to compute  $\bar{\xi}_\rho(r, z)$ . The cosmological parameters used in our chosen model are  $\Omega_m(z=0) = 0.3$ ,  $\Omega_\Lambda(z=0) = 0.7$ ,  $\Gamma = 0.17$  and  $\sigma_8 = 0.84$ . We find the simple form,

$$\bar{\xi}_\rho(r, z) = [A \exp(Bz) + C] \bar{\xi}_\rho(r, z=0) \quad (17)$$

where  $A = 0.2041$ ,  $B = -1.082$ , and  $C = 0.018$  models the evolution of  $\bar{\xi}_\rho(r, z)$  extremely well, for  $1 h^{-1}$  Mpc  $\leq s \leq 20 h^{-1}$  Mpc.

At the mean redshift of our survey,  $\Omega_m(z = 1.27) = 0.81$ , we find  $b_Q(z = 1.27) = 2.06 \pm 0.03$  from the full SDSS DR5Q UNIFORM sample. The values for our redshift sub-samples are shown as filled circles in Fig. 12 and are given in Table 3. We estimate our errors by using the variations in  $\bar{\xi}(s)$  from our 21 jackknife estimates, scaled using the number of  $DD$  pairs in each redshift slice subsample. Previous measurements from the 2QZ Survey (filled green circles, Croom et al. 2005), the 2SLAQ QSO Survey (open black stars, da Ângela et al. 2008) and photometrically selected SDSS quasars (filled red squares, Myers et al. 2007) are again in excellent agreement with our data. We compare these bias estimates with various models in Section 5.4.

Having measured  $b(z)$  and assuming a cosmological model, we can infer the parameter  $\beta(z)$  using equation 12. The space density of quasars is much smaller than that of galaxies, so the errors on the clustering measurement (e.g.  $\xi(r_p, \pi)$ ) are much larger than for galaxy surveys (cf. Hawkins et al. 2003; Zehavi et al. 2005; Ross et al. 2007; Guzzo et al. 2008). Furthermore, as discussed in Section 4.2, we have not included the effects from the ‘‘Fingers-of-God’’ in the present calculation of  $\beta(z)$  but the peculiar velocities at small (transverse  $r_p$ ) scales will very strongly affect the measured redshift distortion value of  $\beta$  (Fisher et al. 1994; da Ângela et al. 2005). With  $b(z = 1.27) = 2.06 \pm 0.03$  and  $\Omega_m(z = 1.27) = 0.81$  we find  $\beta(z = 1.27) = 0.43$ , but for the reasons given above we present no formal error bar. This result is consistent with the values of  $\beta(z)$ , measured from redshift-space distortions in the 2QZ survey,  $\beta(z = 1.4) = 0.45^{+0.09}_{-0.11}$  (Outram et al. 2004) and  $\beta(z = 1.4) = 0.50^{+0.13}_{-0.15}$  (da Ângela et al. 2005).

#### 5.4. Models of bias and dark matter halo mass estimation

We now compare our bias measurements with those of recent models for the relationship of quasars to their host haloes.

The fitting formula of Jing (1998), which is derived from  $N$ -body simulations and assumes spherical collapse for the formation of haloes, is plotted in Fig. 12 (dashed lines) with the assumed halo masses (top to bottom)  $M_{\text{DMH}} = 2.0 \times 10^{12} h^{-1} M_\odot$ ,  $1.0 \times 10^{12} h^{-1} M_\odot$  and  $5.0 \times 10^{11} h^{-1} M_\odot$ , respectively. With the Jing (1998) model, we find the halo mass at which a ‘typical SDSS quasar’ inhabits remains *constant* (given associated errors) with redshift, at a value of a  $M_{\text{DMH}} \sim 1 \times 10^{12} h^{-1} M_\odot$ .

By incorporating the effects of non-spherical collapse for the formation of dark matter haloes, Sheth et al. (2001) provide fitting functions for the halo bias, which are also shown in Fig. 12 (solid lines). Here, the three assumed halo masses of (top to bottom)  $M_{\text{DMH}} = 4.0 \times$

$10^{12} h^{-1} M_\odot$ ,  $2.0 \times 10^{12} h^{-1} M_\odot$  and  $5.0 \times 10^{11} h^{-1} M_\odot$ , respectively are plotted. Comparing our results to the Sheth et al. (2001) models, we again find the host dark matter halo mass is constant with redshift, at a value of a  $M_{\text{DMH}} \sim 2 \times 10^{12} h^{-1} M_\odot$ ; this mass does not significantly change from  $z \sim 2.5$  to the present day, i.e. over 80% the assumed age of the Universe. Therefore, as dark matter halo masses generally grow with time, the ratio of the halo mass for a typical quasar to the mean halo mass at the same epoch drops as one approaches redshift  $z = 0$ . Since the ‘non-spherical collapse’ model is likely to be more realistic, and for ease of comparison with previous results, we quote the Sheth et al. (2001) halo mass value from here on.

Our values of halo masses of  $M_{\text{DMH}} \sim 2 \times 10^{12} h^{-1} M_\odot$  found for the SDSS quasars compare very well to those of Padmanabhan et al. (2008), who find a similar value for low ( $z < 0.6$ ) SDSS quasars. Croom et al. (2005) also find a constant, but slightly higher value of  $M_{\text{DMH}} = 3.0 \pm 1.6 \times 10^{12} h^{-1} M_\odot$ , by using the Sheth et al. (2001) prescription, over the redshift range  $0.3 < z < 2.9$  for the 2QZ. da Ângela et al. (2008) also find  $M_{\text{DMH}} \sim 3.0 \times 10^{12} h^{-1} M_\odot$  but recall this analysis uses data from both the 2QZ and 2SLAQ QSO surveys. Myers et al. (2007) provide halo masses (also using the Sheth et al. (2001) prescription) for two cosmologies and we take their  $\Gamma = 0.15$ ,  $\sigma_8 = 0.8$  model as this is closer to our own assumed cosmology. Again no evolution in the halo mass is found from  $z \sim 2.5$ , but the Myers et al. (2007) value of  $M_{\text{DMH}} = (5.2 \pm 0.6) \times 10^{12} h^{-1} M_\odot$  is appreciably higher than our results. Porciani et al. (2004) applying a halo occupation distribution (HOD) model to the 2QZ data, find  $M_{\text{DMH}} \sim 1 \times 10^{13} h^{-1} M_\odot$ . This is roughly an order of magnitude higher than the values we report and indeed at least double that of the other values found in the literature for luminous quasars. The Porciani et al. (2004) value is in line with  $M_{\text{DMH}} \sim 1 - 2 \times 10^{13} h^{-1} M_\odot$  which is the halo mass found for both the most luminous quasars or those that are FIRST-detected (i.e. radio loud) in the SDSS DR5Q at  $z < 2.5$  (Shen et al. 2009). Thus we suggest some caution should be taken in the Porciani et al. (2004) result but note that these authors use the halo bias formula from Sheth & Tormen (1999) which is likely to contribute to some of the discrepancy. Shen et al. (2007) find a *minimum* halo mass of  $M_{\text{DMH}} = 2 - 3 \times 10^{12} h^{-1} M_\odot$ , and  $M_{\text{DMH}} = 4 - 6 \times 10^{12} h^{-1} M_\odot$ , for the very luminous, higher clustered, high redshift SDSS quasars at  $2.9 \leq z \leq 3.5$  and  $z \geq 3.5$  respectively.

Using semi-analytic models for BH accretion and quasar emission developed on top of the Millennium Simulation (Springel et al. 2005), Bonoli et al. (2008) provide a direct theoretical companion work to our observational study and that of Shen et al. (2009). These authors reproduce our findings that luminous AGNs i.e. the SDSS  $z < 2.2$  quasars (with  $L_{\text{Bol}} \sim L^*$ ), are hosted by dark matter haloes with a narrow mass range centred around a few  $10^{12} h^{-1} M_\odot$ . The results of Bonoli et al. (2008, e.g. their Fig. 13) might however suggest a slightly stronger redshift evolution for the host halo mass at  $z < 2$  than is given by our observational data, but this is hard to confirm given the associated errors on both the observational data and theoretical models.

We next compare with the models of Hopkins et al.

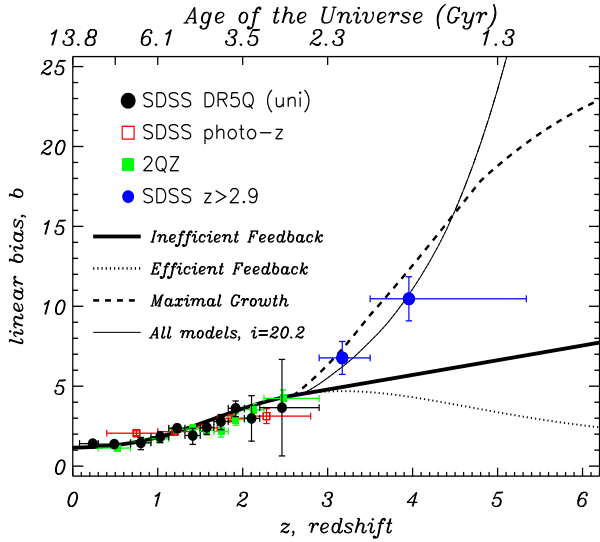


FIG. 13.— Evolution of the linear bias of quasars,  $b_Q$ , with redshift to  $z = 6$ . Filled (black) circles, this work; filled (green) squares, Croom et al. (2005); open (red) squares, Myers et al. (2007); filled (blue) circles, Shen et al. (2007); The *thin* solid line shows the behaviour for all of the three Hopkins et al. (2007) models at  $i = 20.2$ , with these models having identical behaviour for  $b(z)$ . The *thick* solid line shows the “Inefficient feedback” model for a magnitude limited survey of  $i = 30$  i.e., a truly “complete” survey. The dotted line is for the “Efficient feedback” model (at  $i = 30$ ) and the “Maximal growth” model is given by the dashed line (also for  $i = 30$ ).

(2007, e.g. their Fig. 13). Here three models are described for the feeding of quasars. All the models have the same  $z < 2$  behaviour, as in each case quasars are said to “shut down”, i.e. there is no accretion onto the central SMBH at  $z \lesssim 2$ .

The first of the Hopkins et al. (2007) models is the “Inefficient Feedback” model, whose predictions are given by the solid lines in Fig. 13. Here  $z > 6$  quasars grow either continuously or episodically with their host systems until the epoch where “downsizing” begins (i.e.  $z \sim 2$ ). Thus, at redshifts  $z > 2$  feedback from quasar activity is insufficient to completely shut down the quasar, hence the term “inefficient feedback”.

The second of the Hopkins et al. (2007) models is the “Extreme Feedback” model, represented by the dotted line in Fig. 13. Here each SMBH only experiences one episode of quasar activity, after which the quasar completely shuts down, even if this occurs at high ( $z > 2$ ) redshifts. BH growth will cease after this one-off quasar phase. If objects cannot grow after their quasar epoch even at high redshifts, then the subsequent decline of the break in the QLF at  $L = L^*$  traces a decline in characteristic active masses, and the linear bias of active systems “turns over”.

The third of the Hopkins et al. (2007) models is the “Maximal Growth” model, represented by the dashed line in Fig. 13. In this model the BHs grow mass at their Eddington rate until  $z \sim 2$ . For example, a  $\sim 10^8 M_\odot$  BH at  $z \sim 6$  will grow to  $\sim 5 \times 10^9 M_\odot$  at  $z \sim 2$  at which point the growth ceases and the BH mass remains constant.

The limiting factor in our ability to discriminate between models is the dynamic range in luminosity and redshift. We thus extend our redshift baseline up to  $z = 6$  in

Figure 13 and now also plot the bias estimates for the  $z > 2.9$  SDSS quasar clustering measurements of Shen et al. (2007), given by the filled blue circles, where we use their measured values of  $\xi_Q(s, \bar{z} = 3.2) = 1.23 \pm 0.35$  and  $\xi_Q(s, \bar{z} = 4.0) = 2.41 \pm 0.59$  with our equation (16) to estimate the bias.

A magnitude limit of  $m_i < 20.2$  is chosen for the models to match the SDSS high-redshift quasar selection. As can be seen in Fig. 13, all models match the observational clustering data well at  $z < 2$ . However, at this magnitude limit the QLF break luminosity  $L^*$  is only marginally resolved at  $z \sim 2 - 3$  (e.g. Richards et al. 2006); above this redshift surveys are systematically biased to more massive  $L > L^*$  BHs with higher clustering and larger linear biases. Subsequently, the models with the  $m_i < 20.2$  limit have no discriminating power at  $z > 2$ , and the predicted behaviour for the linear bias from the “Inefficient”, “Efficient” and “Maximal Growth” models is identical. To break this degeneracy, deeper observational data at high redshift will be needed. Fortunately, these data should be in hand within the next few years, which will be able to discriminate and test these models, such as those with an effectively infinitely deep flux limit of  $i = 30$  that are also plotted in Fig. 13. Therefore, further investigations into the link between AGN/quasar activity, the build-up of SMBH mass and the formation and evolution of quasars and galaxies using clustering measurements are left to future investigations.

## 6. CONCLUSIONS

We have calculated the two-point correlation function using a homogeneous sample of 30 239 quasars from the Fifth Data release of the SDSS Quasar Survey, covering a solid angle of  $\approx 4000 \text{ deg}^2$ , a redshift range of  $0.3 \leq z \leq 2.2$  and thus representing a measurement over the largest volume of the Universe ever sampled at  $25 h^{-3} \text{ Gpc}^3$  (comoving) assuming the current  $\Lambda\text{CDM}$  cosmology. We find that:

- The two-point redshift-space correlation function is adequately described by a single power-law of the form  $\xi = (s/s_0)^{-\gamma}$  where  $s_0 = 5.95 \pm 0.45 h^{-1} \text{ Mpc}$  and  $\gamma_s = 1.16^{+0.11}_{-0.16}$  over  $1 \leq s \leq 25 h^{-1} \text{ Mpc}$ .
- We see no evidence for significant clustering ( $\xi(s) > 0$ ) at scales of  $s > 100 h^{-1} \text{ Mpc}$ .
- There are strong redshift-space distortions present in the 2-D  $\xi(r_p, \pi)$  measurement, with “Fingers of God” seen at small scales. However, these are most likely primarily dominated by redshift errors.
- We find no significant evolution of clustering amplitude of the SDSS quasars to  $z \sim 2.5$ , though we note that the luminosity threshold of the sample also increases steadily with redshift and the clustering strength does increase at higher redshift. This is investigated further in Shen et al. (2009).
- Comparing our results with recent deep X-ray surveys, our clustering measurements are in reasonable agreement in some cases e.g. Gilli et al. (2005), Miyaji et al. (2007) and XMM-COSMOS Gilli et al. (2008) but significantly lower correlation

lengths in others. However, there is still much scatter in the deep X-ray data, potentially due to cosmic variance and the small samples used for these analyses.

- The linear bias for SDSS quasars over the redshift range of  $0.3 \leq z \leq 2.2$  is  $b(z = 1.27) = 2.06 \pm 0.03$ . Using this bias measurement and assuming  $\Omega_m(z = 1.27) = 0.81$ , but not taking into account the effects of small-scale redshift-space distortions, we find  $\beta(z = 1.27) = 0.43$ . Both these values are consistent with measurements from previous surveys, i.e. the 2QZ.
- Using models which relate dark halo mass to clustering strength (e.g. Sheth et al. 2001), we find that the dark halo mass at which a ‘typical SDSS quasar’ resides remains roughly constant with redshift at  $M_{\text{DMH}} \sim 2 \times 10^{12} h^{-1} M_{\odot}$ . This non-evolution of quasar host halo mass agrees very well with previous studies by e.g. Croom et al. (2005) and da Ângela et al. (2008). Therefore, as dark halo masses grow with time, the ratio of the typical halo mass for a quasar to other haloes at the same epoch drops with redshift.
- Using current clustering data, we are unable to discriminate between the “Inefficient Feedback”, “Efficient Feedback” and “Maximal Growth” models proposed by Hopkins et al. (2007) at  $z < 2$ . The measured evolution of the clustering amplitude is in reasonable agreement with recent theoretical models, although measurements to fainter limits will be needed to distinguish different scenarios for quasar feeding and black hole growth.

Shen et al. (2009) study the clustering properties of DR5 quasars as a function of luminosity, virial mass, colour and radio loudness.

The SDSS is now complete and the final quasar catalogue from Data Release 7 (Abazajian et al. 2008) is being prepared. This catalogue should be a  $\sim 60\%$  increment over DR5, containing about 130,000 quasars with spectroscopic observations, and will almost double the number of quasars in the UNIFORM sub-sample. DR7 will not change the luminosity dynamic range of the SDSS quasar survey but with final analysis of data from, e.g., the 2SLAQ QSO Survey (Croom et al. 2008), and extension of the deep X-ray surveys (e.g. Extended CDFS, Lehmer et al. 2005), connections between the “luminous” and “average” AGN luminosity regimes should begin to converge.

Looking further ahead, even with the dramatic increase in data that surveys such as the 2QZ and SDSS have provided, the desire to increase dynamic range continues. For instance, due to the steepness of the faint end

of the quasar luminosity function (Hopkins et al. 2007), low luminosity quasars should be relatively plentiful, as long as one can identify these objects. This will be a strong challenge for the next generation of quasar redshift surveys e.g. the Baryon Oscillation Spectroscopic Survey (BOSS, Schlegel et al. 2007) but one that will lead to another significant increase in our understanding of quasars, supermassive black holes, galaxy formation and evolution and the properties of the Universe.

#### ACKNOWLEDGMENTS

This work was partially supported by National Science Foundation grants AST-0607634 (N.P.R. and D.P.S.) and AST-0707266 (Y.S. and M.A.S.). We warmly thank S.M. Croom for providing the 2QZ data points, S. Basialakos, A. Lidz and P. Hopkins for providing their model data shown in Section 5 and R. Gilli for allowing us to report the most recent XMM-Newton COSMOS results prior to publication. P. Allen, W.N. Brandt, A.D. Myers and R. Nemmen provided very useful discussion. The JavaScript Cosmology Calculator was used whilst preparing this paper (Wright 2006). This research made use of the NASA Astrophysics Data System. The data and code used will become publicly available at <http://www.astro.psu.edu/users/npr/DR5/> upon publication of this paper. We thank the anonymous referee for comments that improved this work.

Funding for the SDSS and SDSS-II has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation, the U.S. Department of Energy, the National Aeronautics and Space Administration, the Japanese Monbukagakusho, the Max Planck Society, and the Higher Education Funding Council for England. The SDSS Web Site is <http://www.sdss.org/>.

The SDSS is managed by the Astrophysical Research Consortium for the Participating Institutions. The Participating Institutions are the American Museum of Natural History, Astrophysical Institute Potsdam, University of Basel, University of Cambridge, Case Western Reserve University, University of Chicago, Drexel University, Fermilab, the Institute for Advanced Study, the Japan Participation Group, Johns Hopkins University, the Joint Institute for Nuclear Astrophysics, the Kavli Institute for Particle Astrophysics and Cosmology, the Korean Scientist Group, the Chinese Academy of Sciences (LAMOST), Los Alamos National Laboratory, the Max-Planck-Institute for Astronomy (MPIA), the Max-Planck-Institute for Astrophysics (MPA), New Mexico State University, Ohio State University, University of Pittsburgh, University of Portsmouth, Princeton University, the United States Naval Observatory, and the University of Washington.

#### APPENDIX

##### A. SDSS TECHNICAL DETAILS

###### A.1 The Catalog Archive Server

The SDSS database can be interrogated through the Catalog Archive Server<sup>12</sup> (CAS) using standard Structured Query Language (SQL) queries. When querying the CAS, one has a choice to query either the **best** or **target** database

<sup>12</sup> <http://cas.sdss.org>



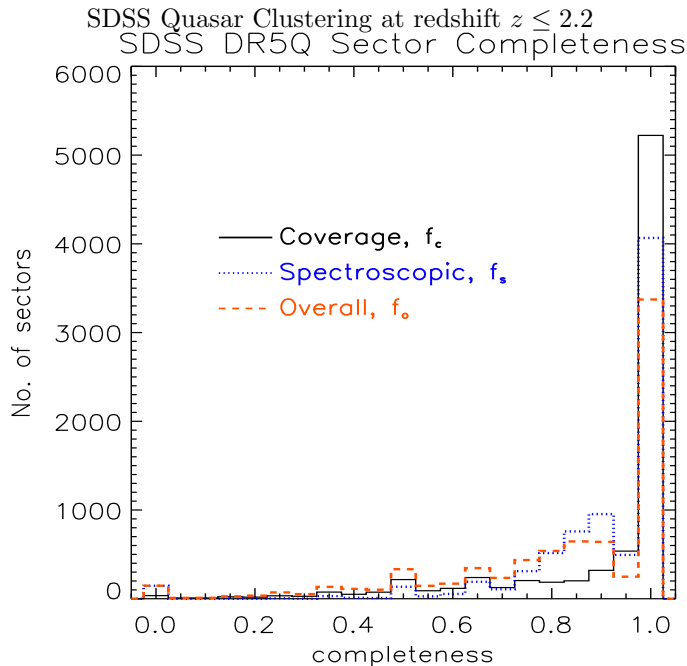


FIG. 14.— Histogram showing the completeness of the DR5 Quasar survey by sector. The solid (orange) line shows completeness distribution for all 7814 sectors, while the dotted (blue) line shows the completeness distribution for the 5831 sectors which have one or more POAs in them. The summed area of sectors with given completenesses is shown by the dashed line.

for a given Data Release (in our case, DR5). The former database contains information on all the photometric and spectroscopic objects obtained using the latest (and thus the “best”) versions of the data reduction and analysis pipelines (Section 3, Abazajian et al. 2004). The **target** database however, contains the information on objects available at the time that the targeting algorithm pipelines were run. An object’s magnitude or colour can be subtly different between target allocation and the most recent data processing, and some objects change their target selection status between the two. More details regarding the CAS, **best** and **target** are given in the relevant SDSS Data Release papers (Stoughton et al. 2002; Abazajian et al. 2004; Adelman-McCarthy et al. 2007).

In order to create a statistical data sample, or to mimic it for a comparative ‘random’ sample, we need to know the properties of our chosen objects *at the time of targeting*, i.e. which objects were selected as quasar candidates. Thus here, we only use information from **target**.

### A.2 SDSS Survey Geometry

As mentioned in Section 3.1 and 3.2, in order to calculate the 2PCF, one needs to assemble a “random” sample which reproduces the angular selection function (“the mask”) and the radial distribution of the quasar data. In this section we describe the steps required to define the mask over which our sample was defined.

The first SQL query we run simply asks the CAS to return all the objects in the Photometric database that were targetted as “primary” candidate quasars. When run on DR5, this returns 203 185 objects from the PhotoObjAll table.

We next calculate which primary ‘PhotoObjAll’ objects (POAs) fall within the spectroscopic survey plate boundaries. We do not use any of the “Extra”, “Special”, or “ExtraSpecial” plates for our analysis as these plates were not targetted with the normal quasar algorithm, or are duplicates (Adelman-McCarthy et al. 2006). There are 145 524 POA objects that fall within 1.49 degrees of a given DR5 plate centre, noting that since plates overlap due to the tiling scheme, an object can be in more than one plate.

Of these 145,524 objects, 11,336 are duplicate objects, defined as being within 1” of another object in the catalogue. Of these 134,188 unique objects, we would next like to know how many were (a) designated as spectroscopic (“tilable”) targets by the process of ‘Tiling’ and (b) allocated fibres. A tile is a 1.49 degree radius circle on the sky which contains the locations of up to 592 tilable targets and other science targets (the other 48 fibres are assigned to calibration targets and blank sky). For each tile a physical aluminum plate is created. The plates will have holes drilled in them for fibres to be plugged, in order to observe the tiled targets. The goal of the tiling procedure, described in detail by Blanton et al. (2003)<sup>13</sup>, is to maximise the total number of targets assigned fibres. Due to the large-scale structure in the quasar/galaxy distribution the procedure overlaps tiles with one other.

As described in Blanton et al. (2003), Tegmark et al. (2004), Blanton et al. (2005) and Percival et al. (2007), a “sector” is defined as a set of tile overlap regions (spherical polygons) observed by a unique combination of tiles and survey “chunks”. A ‘chunk’ is a unit of SDSS imaging data and is a part of an SDSS ‘stripe’, which is a 2.5° wide cylindrical segment aligned along a great circle between the survey poles. These sectors are the natural areas on which to define the completeness of our sample. There are 7 814 sectors for DR5, 5 831 of which have one or more POA objects in them. Using the RegionID field in the **target** table (which gives the sector identification number if set,

<sup>13</sup> see also <http://www.sdss.org/dr6/algorithms/tiling.html>

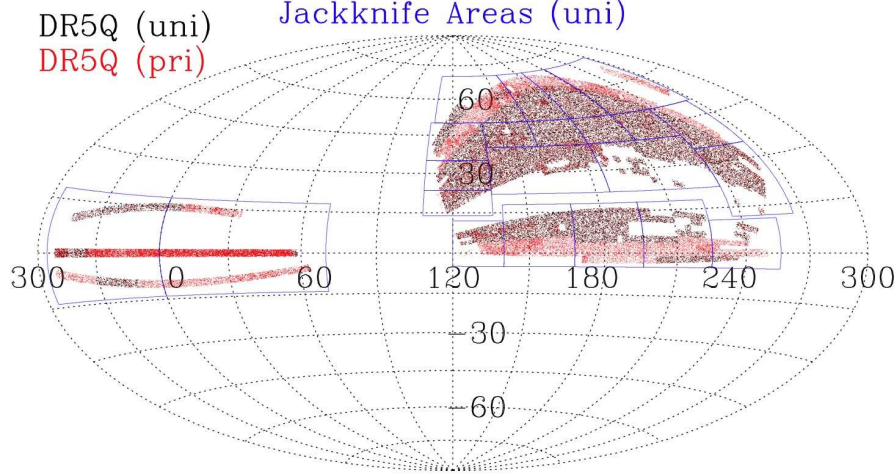


FIG. 15.— Geometry of the SDSS DR5Q Jackknife areas, showing the location of the DR5Q PRIMARY (orange/grey dots) and the UNIFORM (black dots) samples. The jackknife areas were chosen to follow the overall geometry of the SDSS Quasar survey. The number of quasars in each area is approximately equal. Note the sparse coverage of the UNIFORM sample in the Southern Stripes.

zero otherwise) we match the positions (R.A.’s and Decs) of objects in **target** to those that are in PhotoObjAll and the DR5Q.

The efficiency of the quasar targetting algorithm is  $\sim 95\%$  (Vanden Berk et al. 2005). We can define two functions for the primary sample which have dependence on angular position in the sky only in order to calculate the completeness of the survey:

- Coverage Completeness,  $f_Q$ . The coverage completeness is the ratio of the number of quasar targets that are assigned a spectroscopic fibre to the total number of quasar candidates in a given sector. Fibre collisions will be one contributing factor in the coverage completeness.
- Spectroscopic Completeness,  $f_s(\theta)$ . This is the ratio of the number of high-quality spectra obtained in a sector to the number spectroscopically observed. Due to the nature of the SDSS quasar survey, this ratio tends to be very high.

The ‘overall completeness’,  $f_O$ , is defined as  $f_O = f_Q \times f_s$  and the distribution of this overall sector completeness is shown in Fig. 14.

## B. JACKKNIFE ERRORS

Here we follow Scranton et al. (2002, §§3.4.5, 11.3 and their Eq. 10), Zehavi et al. (2002, §3.4 and equation 7) and Myers et al. (2007, Appendix A) to calculate the jackknife error estimates on our quasar clustering data.

Myers et al. (2007) estimate errors using an “inverse variance” weighted jackknife technique. This method divides the data into  $N$  sub-samples and then recalculates the given statistic (e.g.  $\xi(s)$ ) using the Landy-Szalay estimator (equation 5), *leaving out* one sub-sample area at one time. Following their convention we denote subsamples by the subscript  $L$  and recalculate  $\xi(s)_L$  in each jackknife realization via equation 5. The inverse-variance-weighted covariance matrix,  $C(s_i, s_j) = C_{ij}$ , is

$$C_{ij} = \sum_{L=1}^N \sqrt{\frac{RR_L(s_i)}{RR(s_i)}} [\xi_L(s_i) - \xi(s_i)] \sqrt{\frac{RR_L(s_j)}{RR(s_j)}} [\xi_L(s_j) - \xi(s_j)] \quad (\text{B1})$$

where  $\xi$  denotes the correlation function for all data. Jackknife errors  $\sigma_i$  are obtained from the diagonal elements ( $\sigma_i^2 = C_{ii}$ ), and the normalized covariance matrix, also known as the regression matrix, is

$$|C| = \frac{C_{ij}}{\sigma_i \sigma_j} \quad (\text{B2})$$

We divide the sample into 21 sub-samples. The number of subdivisions is chosen such that each represents a cosmologically significant volume, while retaining sufficient numbers of objects that shot noise will not dominate any subsequent analysis. The detailed boundaries of the sub-samples are given in Table 4 and described by Fig. 15.

We find, as in previous quasar clustering work (e.g. Shanks & Boyle 1994; Croom & Shanks 1996), that Poisson errors are a good description on scales where  $DD_q \lesssim N_q$ , where  $N_q$  is the number of quasars in a given sample and  $DD_q$  is the number of quasar pairs in a given bin. On larger scales, the Poisson error tends to underestimate the Jackknife error, see Fig. 17. The scale where  $N_q \approx DD_q$  is  $\sim 70 h^{-1}$  Mpc for the SDSS UNIFORM Quasar sample.

TABLE 4

Region	RA min	RA max	Dec min	Dec max	No. of Quasars	No. of Randoms
N01	120.	140.	-5.	12.	29 445	870 558
N02	140.	168.	-5.	18.	28 456	841 541
N03	168.	196.	-5.	18.	27 904	825 442
N04	196.	225.	-5.	18.	28 717	846 926
N05	225.	256.	-5.	11.	29 891	879 837
N06	108.	136.	14.	23.5	29 614	873 778
N07	108.	136.	23.5	35.	28 646	845 871
N08	136.	186.	22.	40.	26 942	798 307
N09	186.	236.	22.	40.	27 957	820 491
N10	236.	265.	12.	35.	28 253	831 920
N11	108.	136.	35.	50.	29 003	856 576
N12	136.	161.	40.	50.	28 875	855 021
N13	161.	186.	40.	50.	28 857	853 908
N14	186.	211.	40.	50.	28 917	854 055
N15	211.	236.	40.	50.	28 924	854 070
N16	236.	265.	35.	50.	29 246	863 221
N17	110.	161.	50.	70.	29 253	863 420
N18	161.	186.	50.	70.	28 899	853 792
N19	186.	211.	50.	70.	28 911	853 175
N20	211.	268.	50.	70.	29 404	868 561
S	0v305	70v360	-14	18	28 675	842 497

NOTE. — Details of the regions used for the Jackknife subsamples. The “No. of quasars” column gives the number of quasars *left* in the remaining regions when the given region is cut out.

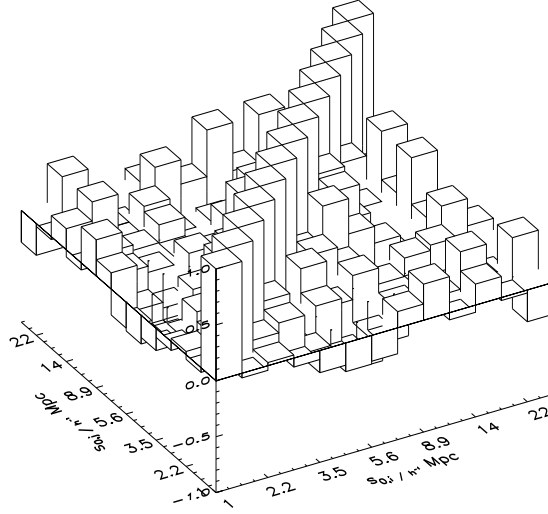


FIG. 16.— The normalised covariance matrix, (the regression matrix) for  $\xi(s)$  from jackknife error analysis on 21 sub-samples of the UNIFORM DR5Q, for scales  $1 h^{-1} \text{ Mpc} < s < 25 h^{-1} \text{ Mpc}$ .

Given the smallness of the off-diagonal elements of the covariance matrix, we measure errors using the diagonal elements only. But here we carry out a check using the full covariance matrix. We fit the observed  $\xi(s)$  to the power law model using the full covariance matrix. We calculate  $\chi^2$  as

$$\chi^2 = \sum_{ij} [\xi(s_i) - \xi_{\text{mod}}(s_i)] C_{ij}^{-1} [\xi(s_j) - \xi_{\text{mod}}(s_j)] \quad (\text{B3})$$

where  $C_{ij}^{-1}$  is the inverse covariance matrix, and  $\xi_{\text{mod}}(s) = (s/s_0)^{-\gamma_s}$  is our model, where we vary  $s_0$  over the range  $s_0 = 0.0 - 15.0 h^{-1} \text{ Mpc}$  in steps of  $0.05 h^{-1} \text{ Mpc}$  and  $\gamma_s$  over the range  $\gamma_s = 0.00 - 3.00$  in steps of  $0.01$ , fitting  $\xi(s)$  on scales from  $1 h^{-1} \text{ Mpc} < s < 25.0 h^{-1} \text{ Mpc}$  scales.

Our estimates of the redshift-space correlation length and power-law slope are now  $s_0 = 6.35^{+0.40}_{-0.35} h^{-1} \text{ Mpc}$  and  $\gamma_s = 1.11^{+0.11}_{-0.08}$  respectively (we found  $s_0 = 5.95 \pm 0.45 h^{-1} \text{ Mpc}$  and  $\gamma_s = 1.16^{+0.11}_{-0.08}$  using the diagonal elements only). However, fitting over  $1.0 h^{-1} \text{ Mpc} < s < 100.0 h^{-1} \text{ Mpc}$  scales, we find there is some tension between the best-fit values given in Section 4.1 of  $s_0 = 5.90 \pm 0.30 h^{-1} \text{ Mpc}$  and  $\gamma_s = 1.57^{+0.04}_{-0.05}$  and the best-fit values using the covariance matrix of  $s_0 = 6.95^{+0.45}_{-0.55} h^{-1} \text{ Mpc}$  and  $\gamma_s = 1.53 \pm 0.09$ . We believe this is due to the noisy matrix inversion, where small values at large scales in the covariance matrix will dominate the signal in the inverse matrix. However, we

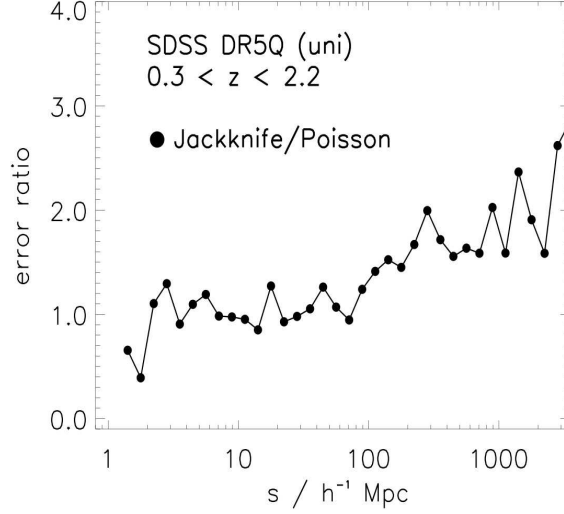


FIG. 17.— Comparison of Poisson and Jackknife errors for the UNIFORM DR5 Quasar sample. The ratio between the Poisson and Jackknife errors (from the diagonal elements of the covariance matrix only) is very close to one at  $s \lesssim 70 h^{-1}$  Mpc, while at  $s \gtrsim 70 h^{-1}$  Mpc, the Poisson errors are  $\sim$  double that of the Jackknives.

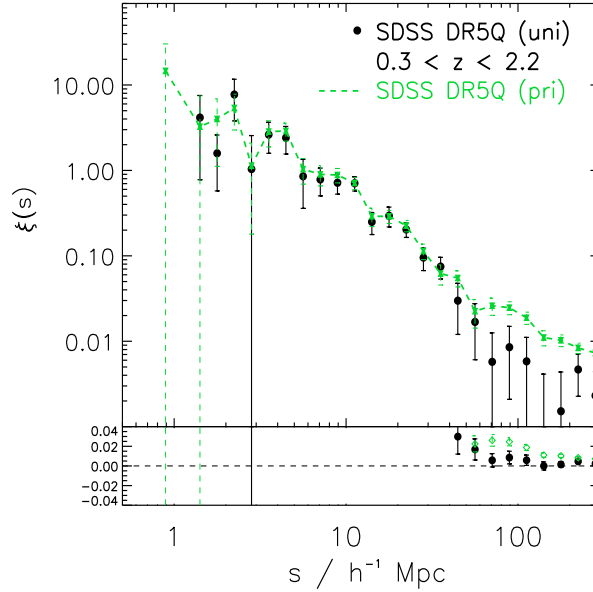


FIG. 18.— The SDSS DR5 Quasar  $\xi(s)$  for the PRIMARY and UNIFORM samples. The lower panel shows the behaviour of  $\xi(s)$  near zero on a linear scale. There is excellent agreement between the two samples at  $s \leq 20 h^{-1}$  Mpc, but the PRIMARY sample exhibits a higher clustering strength at large scales,  $s \geq 40 h^{-1}$  Mpc. This result provides our main motivation for using the UNIFORM sample exclusively in sections 3 and 4.

are confident that using the diagonal elements of the covariance matrix only for our model fits does not change the interpretation of our results.

### C. SYSTEMATICS IN THE SDSS QUASAR 2PCF.

Here we explore the effects of how the various systematic effects in our data, and our methodology affect our correlation results. We shall determine the effects of different quasar samples (Sec. C.1), changing the high-redshift cut (Sec. C.2), the fields which had poor imaging (Sec. C.4), Galactic reddening (Sec. C.5) and fibre collisions (Sec. C.6). We shall report on  $\xi(s)$  and  $w_p(r_p)/r_p$  and find that when using the UNIFORM sample, our overall results (and subsequent interpretations) are robust.

#### C.1 Effects of Different Samples on $\xi(s)$

Figure 18 shows the difference in the redshift-space correlation function,  $\xi(s)$ , for the PRIMARY sample and of the UNIFORM sample using the LS estimator. The two samples are in excellent agreement at small scales,  $s \leq 20 h^{-1}$  Mpc, but the PRIMARY sample exhibits a higher clustering strength at large scales,  $s \geq 40 h^{-1}$  Mpc. One possible explanation for this discrepancy is due to the differing radial distributions in PRIMARY and UNIFORM resulting from the different target selection used before DR2. This result provides our main motivation for using the UNIFORM

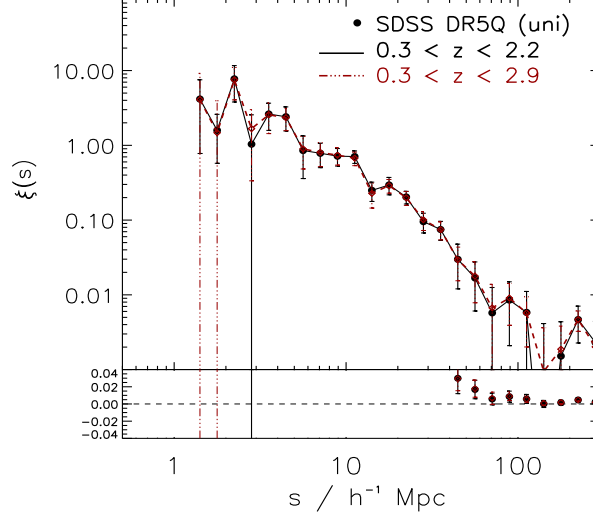


FIG. 19.— The SDSS DR5 Quasar UNIFORM  $\xi(s)$  with upper redshift cut-offs of  $z \leq 2.2$  and  $z \leq 2.9$ . The lower panel shows the behaviour of  $\xi(s)$  near zero on a linear scale. The inclusion of data at  $2.2 \leq z \leq 2.9$  barely changes the measured  $\xi(s)$ .

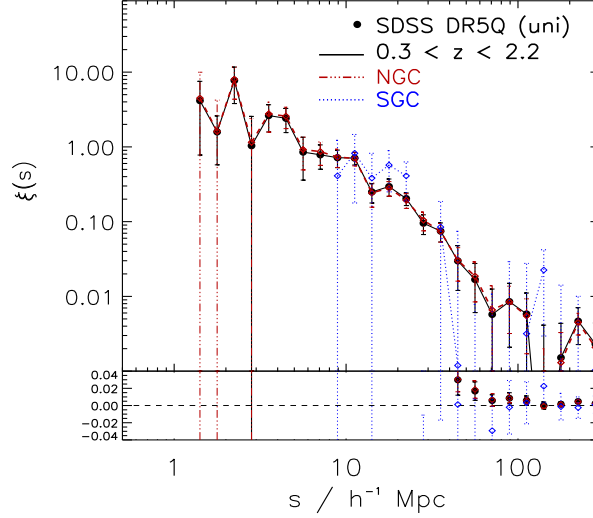


FIG. 20.— The SDSS DR5 Quasar  $\xi(s)$  for the UNIFORM sample with the sample split into the NGC and SGC. The two measurements are in good agreement.

sample exclusively in sections 3 and 4.

### C.2 High redshift cut-off

Figure 19 shows the redshift-space 2-point correlation function  $\xi(s)$  for the UNIFORM sample with the high-redshift cut-off being changed from  $z \leq 2.2$  to  $z \leq 2.9$ . It is reassuring that the change between  $\xi(s)$  is minimal, though this is somewhat unexpected since our the optical selection for the quasar sample is known to be affected between  $z = 2.2$  and  $z = 2.9$  (Richards et al. 2006).

### C.3 The NGC vs. the SGC

Figure 20 shows the redshift-space 2-point correlation function  $\xi(s)$  for the UNIFORM sample, split into quasars from the North Galactic Cap (NGC) and the South Galactic Cap (SGC). Note the data is heavily dominated by the NGC in the UNIFORM sample. There is no detectable signal in the SGC  $\xi(s)$  below  $s \approx 10 h^{-1}$  Mpc and the two measurements are in good agreement.

### C.4 Bad Fields

In the SDSS, a “field” is an image in all five bands, with approximate dimensions of  $13' \times 10'$ . Since the quasar target selection algorithm searches for outliers from the stellar locus in colour space it is very sensitive to data with large photometric errors due to problems in photometric calibration or in point-spread function (PSF) determination (Richards et al. 2006). Thus, using the definitions of “bad fields” given by Richards et al. (2006) and Shen et al. (2007), based on the position of the stars in colour-colour space (Ivezić et al. 2004), we calculate the correlation function both including and excluding data from these areas.



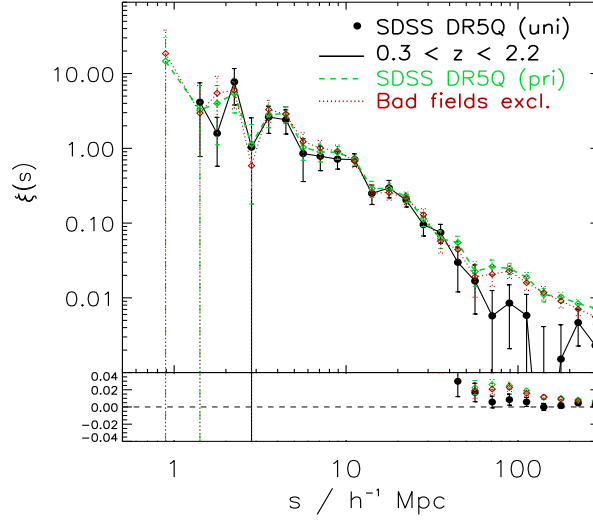


FIG. 21.— The SDSS DR5 Quasar  $\xi(s)$  for the UNIFORM sample is given by the solid (black) circles.  $\xi(s)$  for the PRIMARY sample is given with including, green (solid) line and excluding, dashed (red) line bad imaging fields.

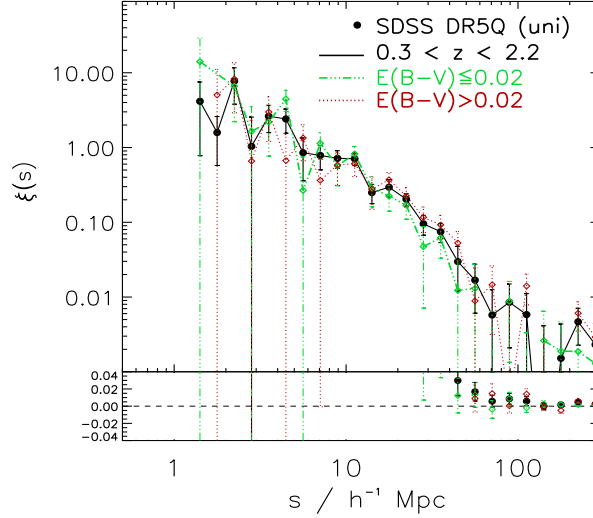


FIG. 22.— The SDSS DR5 Quasar  $\xi(s)$  for the UNIFORM sample with the sample split by  $E(B - V)$ . We see no systematic difference in the clustering signal between the two  $\xi(s)$  measurements that might have been caused due to errors in the reddening correction model.

Figure 21 shows the redshift-space 2-point correlation function  $\xi(s)$  for the UNIFORM sample (solid black circles). Also shown is  $\xi(s)$  for the PRIMARY sample including, (solid green) and excluding, (dashed red) lines, the “Bad Fields” as defined by Shen et al. (2007). Here we can see that there is minimal difference (for the PRIMARY DR5Q sample) between the  $\xi(s)$  estimates when including and excluding the bad fields. This results is reassuring but generally expected since at  $z < 2.2$  quasar selection using the UV excess technique is relatively insensitive to “bad fields”. However, at higher redshift, Shen et al. (2007) found this to be a major issue, where the selection is more sensitive.

### C.5 Reddening

While all selection for the quasar sample is undertaken using dereddened colors (Richards et al. 2002) following the Galactic extinction model of Schlegel et al. (1998), any remaining systematic errors in the reddening model can induce excess power into the clustering in a number of different ways. The most obvious possibility comes from a modulation in the angular density of quasars as a function of position on the sky. In addition the color dependence of the reddening correction may preferentially exclude quasars at specific redshifts. As we currently assume a common  $N(z)$  for all quasars in the UNIFORM sample, an  $N(z)$  that is reddening-dependent can also induce excess clustering. For this analysis we will assume that any artificial signal that might be induced by the reddening correction will scale with the magnitude of the reddening correction itself. We therefore subdivide the UNIFORM quasar sample into two subsets, of approximately equal number, a low reddening sample, with  $0.0028 < E(B - V) \leq 0.0217$ , and a high reddening sample  $0.0217 < E(B - V) \leq 0.2603$ . The reddening estimates are derived from the maps of Schlegel et al. (1998).

Figure 22 shows the redshift-space 2-point correlation function  $\xi(s)$  for the full UNIFORM sample, with the reddening split sub-samples. The low reddening component, dot-dashed (green) line and the high reddening sample, dotted (red)

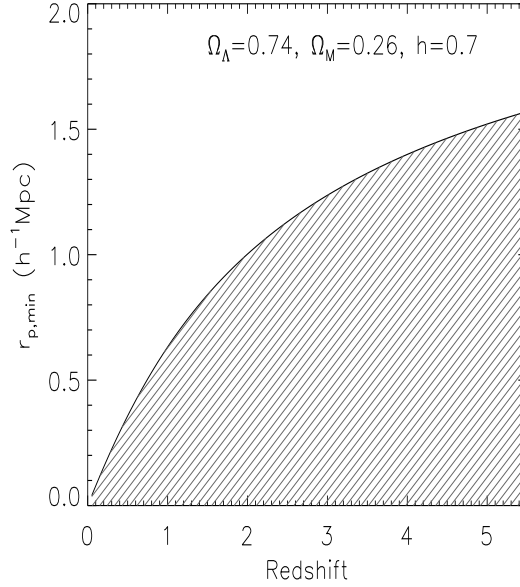


FIG. 23.— The transverse comoving separation corresponding to  $55''$  as a function of redshift. This is the minimal projected comoving separation that can be probed with the SDSS spectroscopic quasar sample as a function of redshift, due to the fibre collision limit of the SDSS spectroscopy.

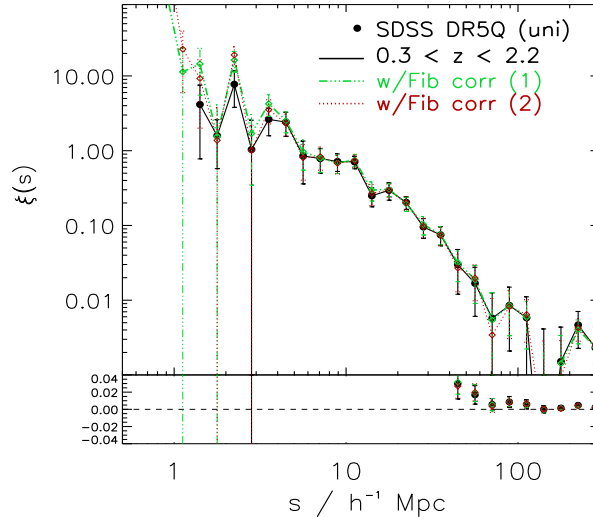


FIG. 24.— The SDSS DR5 Quasar  $\xi(s)$  for the UNIFORM sample: with no fibre collision correction (filled circles); using photometric redshifts for quasar candidates that we not observed due to fibre collisions (green, dot-dashed line) and using the redshifts from the nearest observed quasar for quasar candidates that we not observed due to fibre collisions (red, dotted line). We see very little difference on scales  $s > 5 h^{-1}$  Mpc but do measure increased values of  $\xi(s)$  at  $\sim 1 - 5 h^{-1}$  Mpc.

line are consistent within the errors for all scales out to  $\sim 250 h^{-1}$  Mpc. There is no evidence for a systematic difference in the clustering signal on large scales that might be induced by any modulation due to errors in the reddening correction.

### C.6 Fibre Collisions

Due to the design of the SDSS fibres and plates, no two spectroscopic fibres can be separated by less than  $55''$  (Section 2.1). The corresponding minimum physical separation in  $r_p$  that we can sample is shown by Fig. 23.

To investigate this effect on our correlation function estimates, we find which of the 145 524 POA objects were not observed due to fibre collisions. There are 431 objects that were within  $55''$  of a UNIFORM quasar that were not observed. We assign the “collided” quasar candidates a redshift using two methods. First, (model (1) in Fig. 24 and Fig. 25), using the new version of the SDSS Quasar photometric catalogue, (Richards et al. 2009), we assign the redshift of the nearest photometric quasar to the collided objects. We assume that all the collided objects are in fact quasars, though in reality this is not the case. Second, (model (2) in Fig. 24 and Fig. 25) we assign the collided quasar candidate the redshift from the quasar that “knocked it out”. We then recalculate the 2PCF with these additional objects.

As we can see from Fig. 24, the inclusion of these collided objects makes very little difference to our measurement of

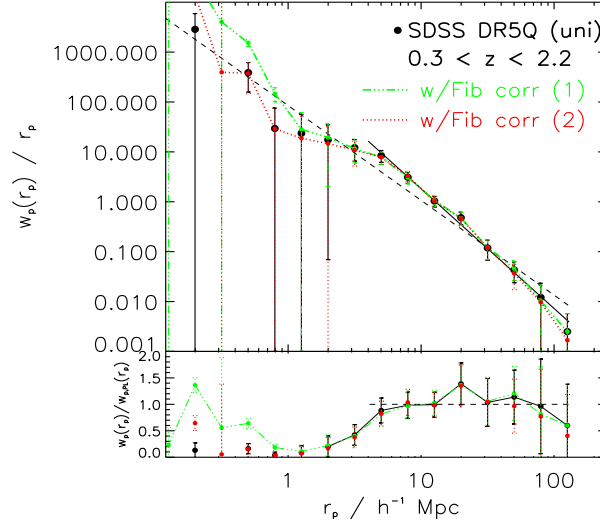


FIG. 25.— The projected correlation function  $w_p(r_p)/r_p$  for the SDSS DR5Q UNIFORM sample with  $0.30 < z < 2.2$  with no fibre collision correction (filled circles); using photometric redshifts for quasar candidates that we not observed due to fibre collisions (green, dot-dashed line) and using the redshifts from the nearest observed quasar for quasar candidates that we not observed due to fibre collisions (red, dotted line). We see very little difference on scales  $r_p > 1 h^{-1}$  Mpc but do measure increased values of  $w_p(r_p)/r_p$  at  $r_p < 1 h^{-1}$  Mpc.

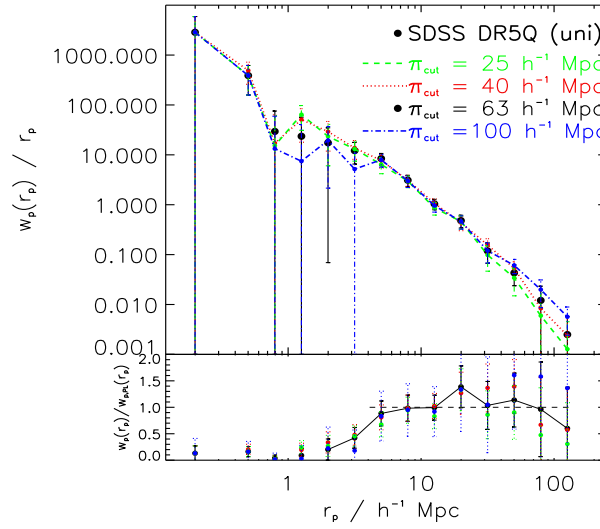


FIG. 26.— The projected correlation function  $w_p(r_p)/r_p$  for the SDSS DR5Q UNIFORM sample with  $0.30 < z < 2.2$ , varying  $\pi_{\max}$  from equation 9. The lower panel has the data divided by the best fit power law from Section 4, with  $r_0 = 8.75 h^{-1}$  Mpc and  $\gamma = 2.40$ .

$\xi(s)$  at scales  $\gtrsim 5 h^{-1}$  Mpc. However, we do measure increased values of  $\xi(s)$  at  $s = 1 - 5 h^{-1}$  Mpc. Therefore, we again fit a single power-law to the data which has been corrected for fibre collisions using the photometric quasar redshifts, over the scales  $1 < s < 25 h^{-1}$  Mpc and find  $s_0 = 6.70^{+0.45}_{-0.30} h^{-1}$  Mpc and  $\gamma_s = 1.29^{+0.12}_{-0.10}$  (cf.  $s_0 = 5.95 \pm 0.45 h^{-1}$  Mpc and  $\gamma_s = 1.16^{+0.11}_{-0.08}$  found in Section 4.1). With the inclusion of more data at small separations, the fibre-corrected  $\xi(s)$  has a higher  $s_0$  value and steeper slope, but we find these results are consistent with our measurement of  $\xi(s)$  without the fibre collision corrections, given the errors.

By examining Fig. 25, we see that fibre collisions do *not* account for the possible break in the slope of  $w_p(r_p)/r_p$  that was discussed in Section 4.3. We are thus satisfied that fibre collisions do not impact the results presented herein and refer the reader to Hennawi et al. (2006) and Myers et al. (2008) for more detailed investigations of quasar clustering and quasar binaries on these very small scales.

### C. 7 Varying $\pi_{\max}$ limits for $w_p(r_p)$

Figure 26 shows the projected correlation function  $w_p(r_p)/r_p$  for the SDSS DR5Q UNIFORM sample with  $0.30 < z < 2.2$ , varying  $\pi_{\max}$  from equation 9. We vary  $\pi_{\max}$  in intervals of  $10^{0.2}$  over the range  $\pi_{\max} = 10^{1.4-2.0} = 25.1 - 100.0 h^{-1}$  Mpc. Although changing the  $\pi_{\max}$  cut does produce a noticeable effect in estimates of  $w_p(r_p)/r_p$ , when fitting our single power law over the scales  $4.0 < r_p < 130.0 h^{-1}$  Mpc, we do not see a significant change in the best-fit  $r_0$  or power-law slope values, with the former constant at  $r_0 \approx 8.3 h^{-1}$  Mpc and the latter constant at  $\gamma \approx 2.3$ . We are therefore confident that the integration limit of  $\pi_{\max} = 63.1 h^{-1}$  Mpc provides a good balance between larger

$\pi$  values which would add noise to our  $w_p(r_p)/r_p$  estimate, and lower  $\pi$  values which might not recover the full signal at the largest separations.

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